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SEAKEEPING AND VIBRATION TESTS OF THE COAST GUARD 110' SURFACE EFFECT SHIP SEA BIRD CLASS (WSES)

Thomas J. Coe

FINAL REPORT
SEPTEMBER 1984

Prepared for:

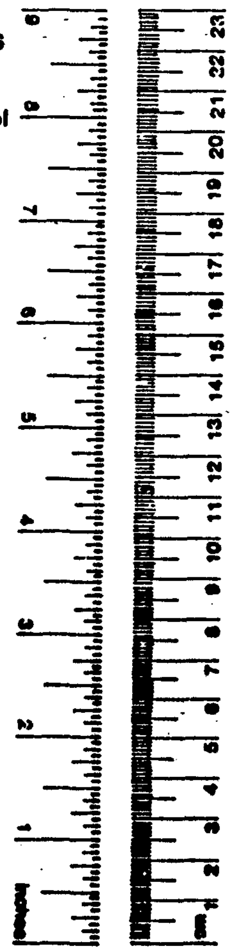
U. S. Department of Transportation
United States Coast Guard
Office of Research and Development
Washington D.C. 20593

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

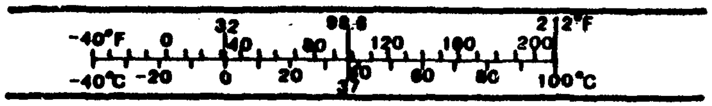
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

Seakeeping and vertical acceleration tests were performed on the U.S. Coast Guard 110' ft Surface Effect Ships USCGC SHEARWATER and USCGC SEA HAWK. Roll, pitch and heave motions were recorded and later analyzed. All motions were averaged by highest one tenth and highest one third single amplitudes. Vertical accelerations were further analyzed using ISO standards to determine the human response and fatigue limits relative to high frequency (1.8 HZ) heave motions encountered. Tests were conducted in 2.5 to 4 foot seas at speeds of 16 to 28 knots.

) See p 1

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INTRODUCTION

The Coast Guard Research and Development Center conducted seakeeping and vibration tests aboard the USCGC SHEARWATER (WSES 3) on 2 December 1982 and aboard the USCGC SEA HAWK (WSES-2) on 25-26 November 1983 and 7-10 August 1984 as part of the Advanced Marine Vehicle Project. These Surface Effect Ships (SES) are two of three stationed in Key West, Florida, in the Coast Guard SES Division. The objective of this technical evaluation was to quantify the ride quality of the Coast Guard 110 SES. This

DESCRIPTION OF THE SES

The United States Coast Guard (USCG) 110-foot surface effect ship (SES) is a high-performance air-cushion-assisted craft, designed for on-cushion speeds of 30 knots in calm water and 25 knots in sea state 3. The ship rides on a drag-reducing cushion of air contained by catamaran-type sidehulls and flexible bow and stern seals. When cruising on cushion, the center portion of the hull is clear of the water and supported by the air cushion, thereby reducing the wetted surface area and decreasing the resistance and enabling higher speed. The ship is also capable of off-cushion operations at low speeds in all sea states. The SHEARWATER was able to maintain 28 knots in 2-foot seas in December 1982; however, recent operations such as the SEA HAWK tests in November 1983 and August 1984 show lower maximum speeds than designed (18-23 knots) are attained. Additional keywords: charts; tables (data);

LIST OF PARTICULARS

Type	Surface Effect Ship - Patrol Vessel
Length, Overall	109 ft 3/4 in.
Length, Cushion	83 ft 2-1/2 in.
Beam, Overall	39 ft 0 in.
Maximum Draft, On Cushion 3.5 Deg Bow-up Trim	5 ft 6 in.
Maximum Draft, Off Cushion, Max, 0 Deg Trim	8 ft 3 in.
Displacement, Light	107.1 long tons (240,008 lb)
Displacement, Max	150 long tons (336,635 lb)
Design Speed, On Cushion	30+ knots, sea state 0 25 knots, sea state 3

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LIST OF PARTICULARS (continued)

Type	Surface Effect Ship - Patrol Vessel
Design Range, On Cushion	1100 nm in sea state 3
Hull Construction	Aluminum
Crew	18 (2 officers, 1 chief petty officer, 15 enlisted)
Main Engines	(2) Detroit Diesel 16V-149TI 1600 shp @ 1900 rpm
Reduction Gears	(2) ZF BW455, 2:1 ratio
Lift Engines	(2) GM 8V-92 diesel 350 shp @ 2100 rpm
Lift Fans	(2) Bell 40-inch-diameter centrifugal fans

EQUIPMENT AND DATA ANALYSIS

Ship motions were measured with a Humphrey, Inc. Ship Motion Package. Roll and pitch angles as well as vertical accelerations were recorded on a STORE 14D analog tape recorder. The motion package was located on the second deck (mess deck) of the SHEARWATER amidships against the aft bulkhead on the centerline (Figure 1). Ship motions were recorded aboard the SHEARWATER at various speeds at five different headings relative to the wave direction, head, bow quarter, beam, stern quarter and following seas. Only head and bow quarter sea runs were conducted during the SEA HAWK tests. Vertical accelerations were measured at two locations on the bridge of the SEA HAWK by a Bruel & Kjaer human response vibration meter and separate vertical accelerometer as seen in Figure 2.

The motion data aboard the SHEARWATER was analyzed in two ways to obtain both magnitude and frequency information. The magnitude of the motions was averaged by digitizing the analog signal with a Hewlett Packard (HP)3437A system voltmeter and searching the record for peaks utilizing a program on a HP9835B computer. The peaks were then sorted from high to low. The average highest one tenth (H 1/10) and one third (H 1/3) values were computed. Roll and pitch angle averages are represented in single amplitude measured from peak to average level list and average trim. Acceleration single amplitude peak values were measured from the average signal level (baseline).

A spectral analysis of the data was also conducted in order to obtain information on motions in the frequency domain. Analysis was conducted

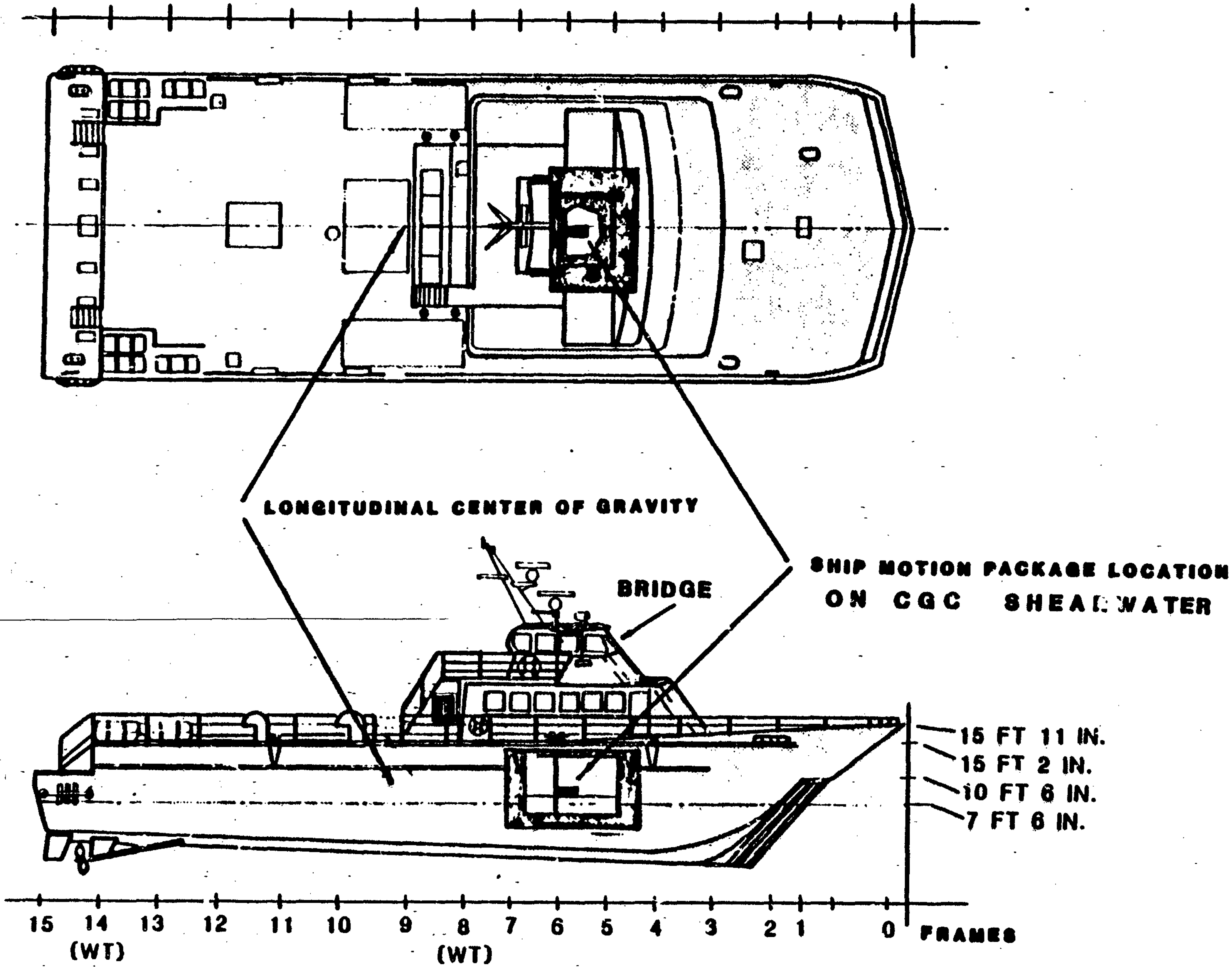


Figure 1 INSTRUMENTATION LOCATION (DEC 1982)

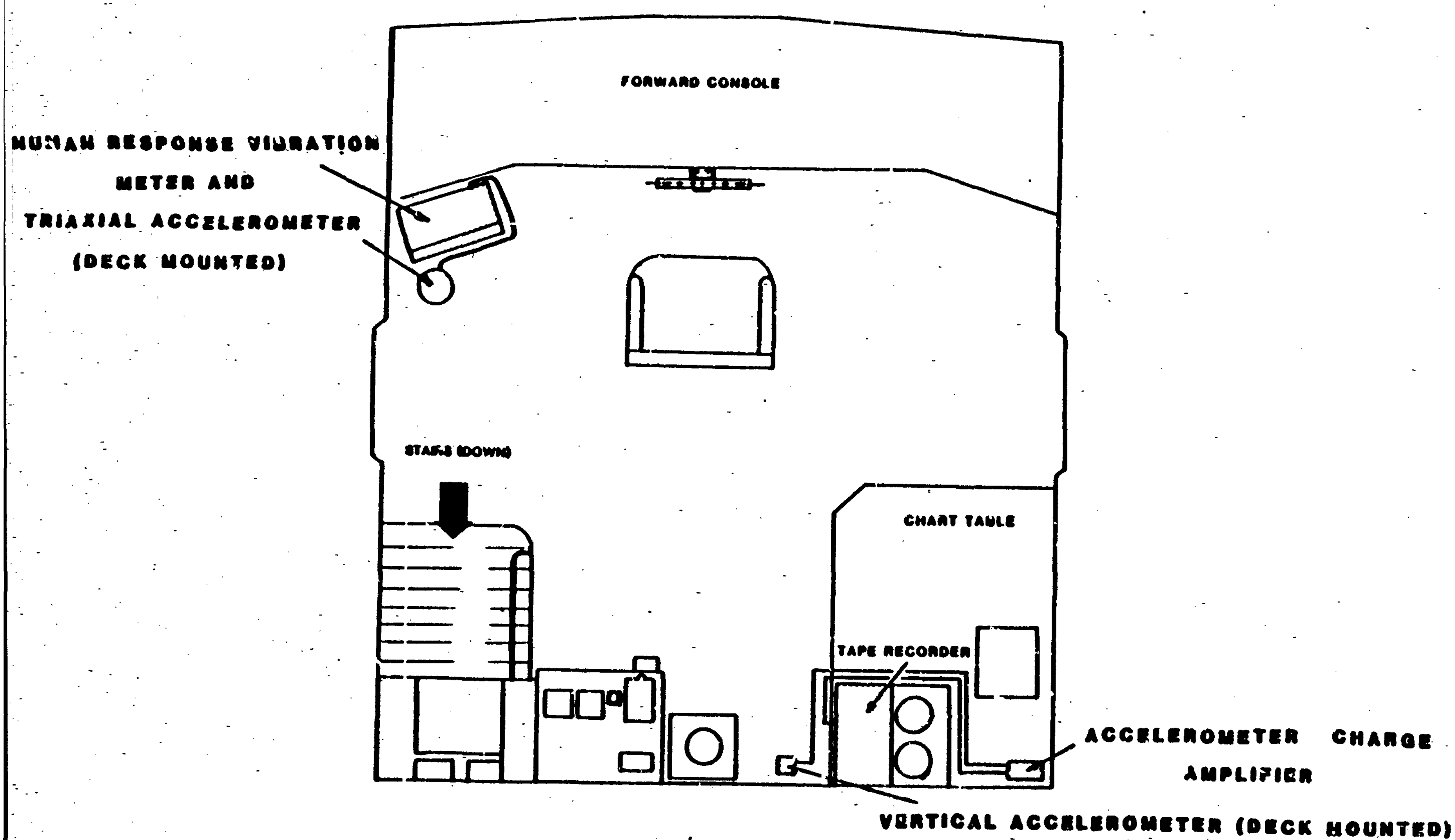


Figure 2 ACCELEROMETER LOCATIONS IN BRIDGE (NOV 1983)
ON CGC SEAHAWK

utilizing a Hewlett Packard 5420A Digital Signal Analyzer. All heave spectra are measured using a random signal type ("hanning" window) which results in a Power Spectral Density (PSD) plot with units of (G's rms)^2/HZ. The advantage of selecting the random signal when dealing with broadband signals is that the results are normalized to the bandwidth of the measurement. This allows for direct comparisons of peak measurements taken on broadband data with different resolutions or bandwidths. More detail of the spectral signal analysis and set up states is presented in Appendix A.

Roll and pitch signals were analyzed using a sinusoidal signal type in order to obtain accurate amplitude measurements. Roll and pitch periods can be extracted from the spectral plots. The frequency of major energy spikes in heave were compared to the frequency of major roll and pitch peaks in order to determine if roll or pitch was strongly coupled to the relatively high heave frequency of 1.8 HZ.

Heave signals were analyzed in accordance with International Organization for Standardization (ISO) standards for evaluation of human exposure to whole-body vibrations, reference (a). A one third octave band analysis was computed from several vertical acceleration narrow band PSD's obtained from both vessel tests using the HP5420A spectral analyzer. Weighting factors were applied in accordance with reference (a). The details of this analysis are outlined in Appendix C.

In order to verify and substantiate the human response measurements made on the spectral analyzer using a discrete 1/3 octave band analysis, another instrument was used during the SEA HAWK tests to document the fatigue effects of the vertical accelerations on people. This instrument, the Bruel & Kjaer Human Response Vibration Meter, Type 2512, computes the percentage that a particular fatigue standard limit is attained with time. It computes this information in real time on board the vessel from input of an accelerometer signal which is sent through frequency-weighted filters specified in reference (a).

The time to reach various fatigue limits aboard the SEA HAWK in 3-4 foot seas is compared utilizing the two methods described, the human response meter and the spectral analysis 1/3 octave method.

A wave height measuring buoy was not utilized to determine the sea state because the tests were preliminary in nature and a short set-up time precluded large instrumentation shipments for the SHEARWATER test. Wave heights were estimated by averaging visual observations from three individuals. Wave height was 2.5 feet caused by localized wind for the SHEARWATER test and estimated significant wave height was 3-4 feet during SEA HAWK tests in November 1983 and 1-2 feet during August 1984 testing. A unidirectional sea state was prevalent during the tests.

SEAKEEPING

Seakeeping tests for the SHEARWATER were conducted at five different orientations (head, bow quarter, beam, stern quarter and following seas) at speeds from 22-28 kts in 2.5' seas. The highest significant roll and pitch angles (H 1/3 amplitudes) were 3.3 and 1.9 degrees, respectively. In general, H 1/3 roll and pitch angle amplitudes were not sensitive to vessel speed or orientation to the major seas as seen in Table 1. Significant roll and pitch amplitudes at 28 knots are displayed on a polar plot in Figures 3 and 4, respectively.

Heave amplitudes are most severe at head seas proceeding at 28 knots;(0.40 G's significant single amplitude accelerations) however, at 22 knots just below hump speed accelerations in general are significantly reduced as seen in the polar plot in Figure 5.

The SEA HAWK also had severe vertical accelerations but at a slower speed in a higher sea state. Significant single amplitude accelerations of 0.32 G's and average highest 1/10 accelerations of 0.44 G's were measured in 3-4 ft. head seas at 17 kts.

FREQUENCY DOMAIN COMPARISONS

In order to gain more insight into the increase of vertical acceleration at higher speeds in head seas various frequency domain measurements are compared.

Heave power spectral density (PSD) plots for the SHEARWATER proceeding at 28 knots in five orientations to the major waves are presented in Figure 6. The major peak of heave energy is between 1.3 to 2.3 HZ for all direction runs. In head seas this peak is the most predominant.

At runs of 22 knots this is not the case as seen in Figure 7. Here just below hump speed the major heave energy peak for all three directions relative to the seas is between 0.2 to 0.8 HZ. This is a "response to the wave encounters" characteristic of a conventional displacement craft at frequencies which are in the motion sickness range.

There is a significant increase of power in the head seas case between 1.3 and 2.3 HZ as the vessel increases speed from 22 to 28 knots, Figure 8. The magnitude of heave power in a bandwidth such as this can be quantified by computing the area under the curve using the power function on the spectral analyzer. Heave power defined as (G's rms)^2 was computed for all heave runs for a 1 HZ band centered around the 1.8 HZ peak. Heave power in that band decreased 88% when speed was reduced from 28 to 22 knots in head seas as seen in Appendix B, Figures B6 and B14. Although the ride is more comfortable and less fatiguing, operation of the vessel at hump speed (22 kts.) is not the most fuel efficient speed as seen by looking at fuel consumption data collected on the CGC DORADO (WSES 1), Figure 9. The power concentrated at 1.8 HZ is also very dependent on the ship's track relative to the sea's direction. There is a 66% decrease of heave rms power when the vessel changes headings from head to bow quartering seas at 28 knots as seen in Figures B6 and B7. All heave PSD plots are presented singularly in Appendix B with and without the 1 HZ bandwidth power calculation centered around 1.8 HZ.

TABLE 1
ONE THIRD AND ONE TENTH HIGHEST MOTIONS
CGC SHEARWATER

Seas 2.5 Feet
2 December 1983

Speed	Heading to Waves	Roll Angle (Deg) Amplitude H 1/10	Roll Angle (Deg) Amplitude H 1/3	Pitch Angle (Deg) Amplitude H 1/10	Pitch Angle (Deg) Amplitude H 1/3	Trim up by Bow	Heave Acceleration G's Amplitude H 1/10	Heave Acceleration G's Amplitude H 1/3
28 kts	Head	3.48	2.77	2.28	1.86	4.2	0.50	0.40
	Bow Qtr	4.07	3.11	2.13	1.77	4.0	0.36	0.29
	Beam	4.03	3.17	2.23	1.85	4.2	0.40	0.31
	Aft Qtr	4.33	3.34	2.11	1.76	3.7	0.39	0.30
	Stern	3.84	3.06	2.27	1.88	3.8	0.43	0.32
25 kts	Bow Qtr	3.89	2.87	2.23	1.84	4.4	0.29	0.24
22 kts	Head	-	-	-	-	-	0.23	0.19
	Bow Qtr	3.11	2.47	2.22	1.79	3.3	0.31	0.25
	Beam	3.37	2.61	2.06	1.74	3.0	0.18	0.16

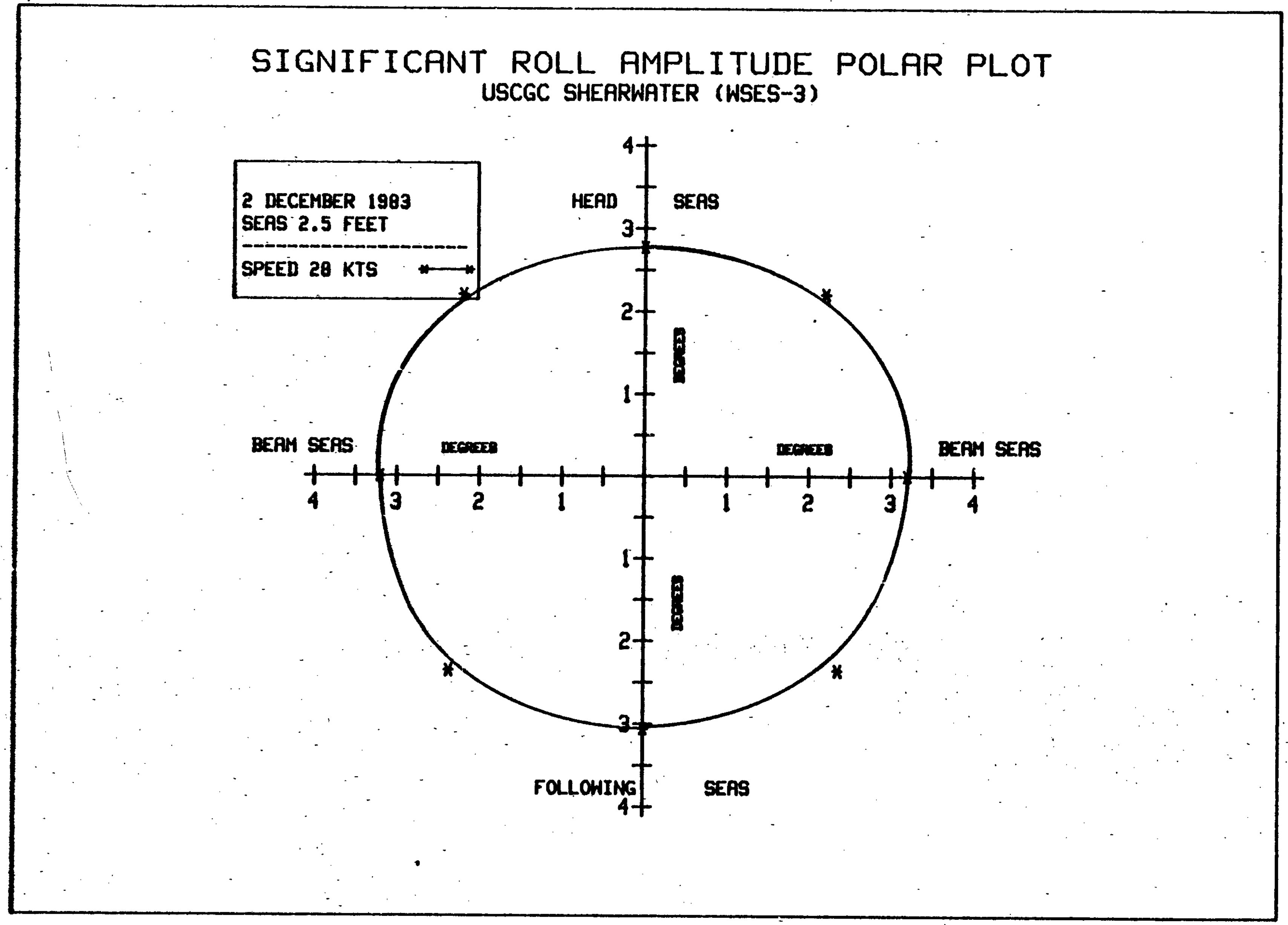


Figure 3. CGC SHEARWATER ROLL AMPLITUDE POLAR PLOT

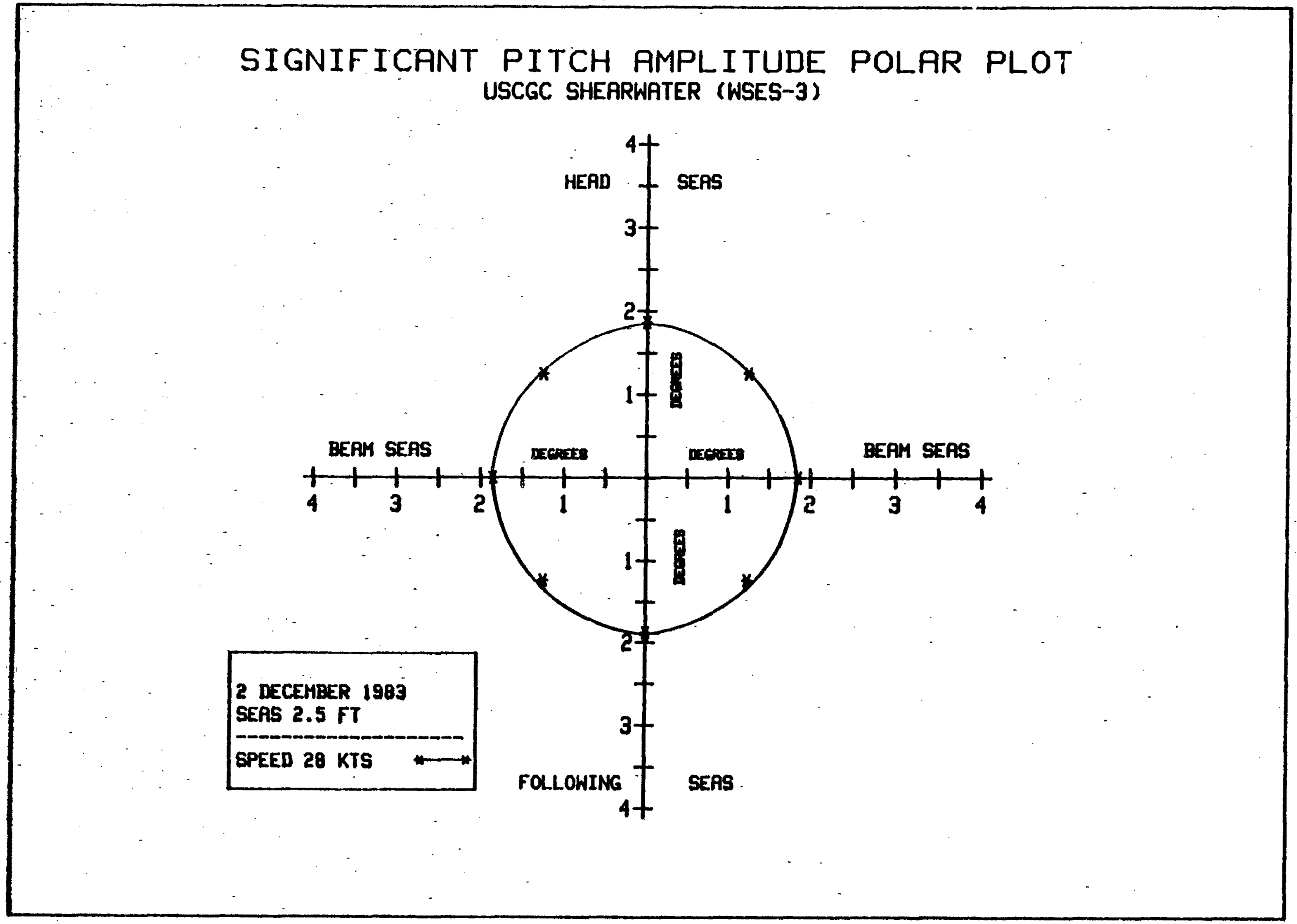


Figure 4. CGC SHEARWATER PITCH AMPLITUDE POLAR PLOT

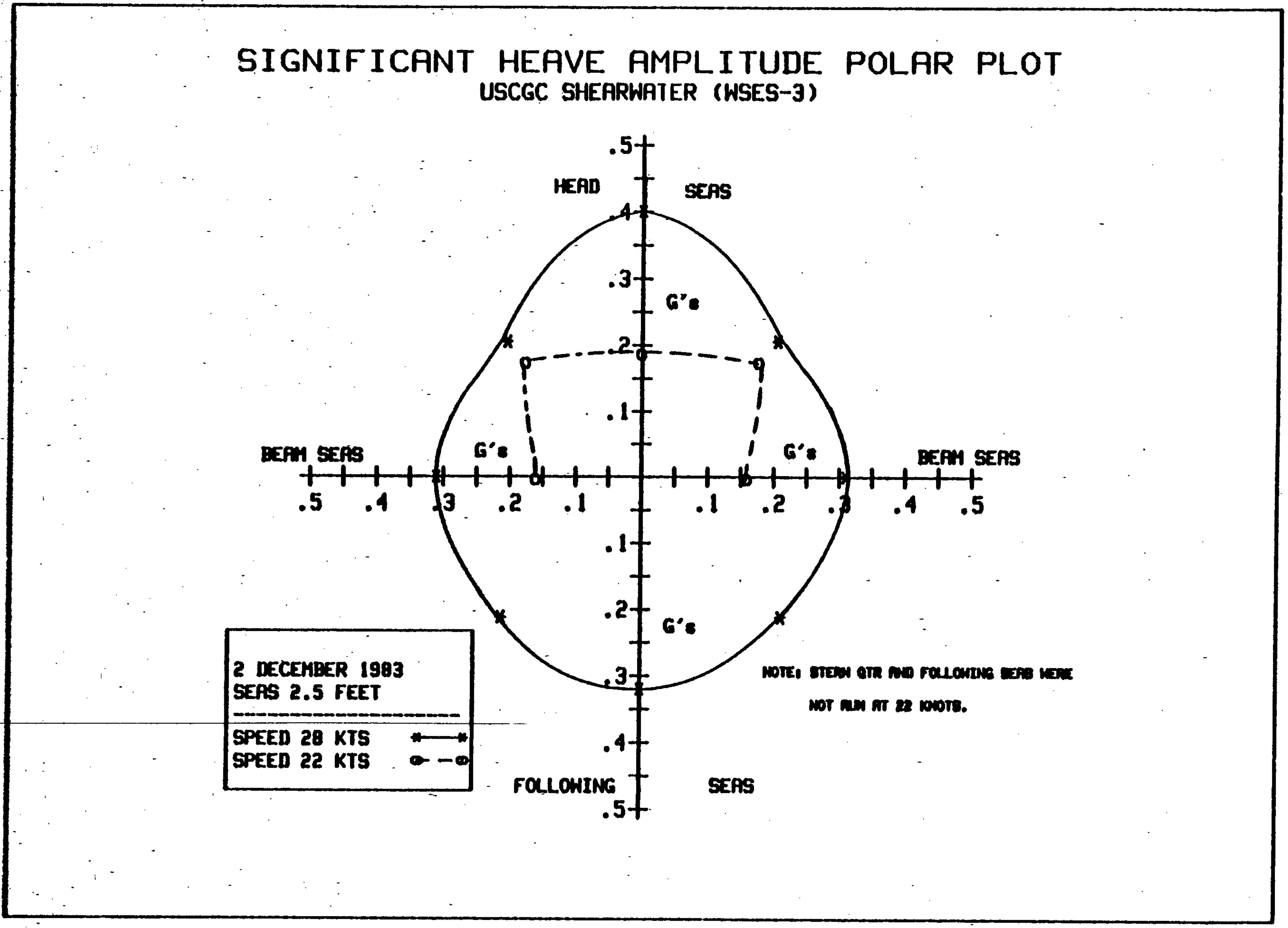


Figure 5. CGC SHEARWATER HEAVE AMPLITUDE POLAR PLOT

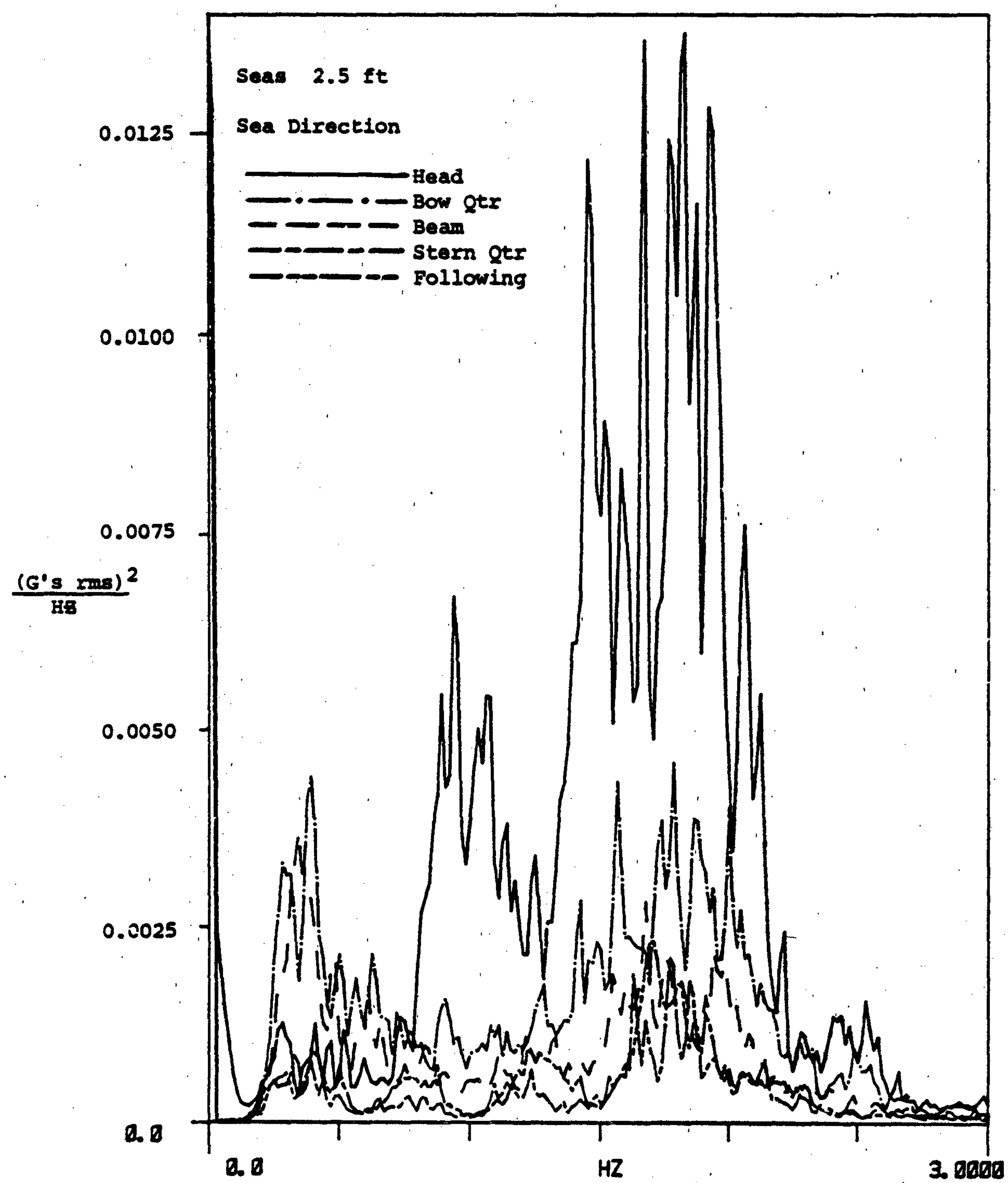


FIGURE 6. HEAVE PSD's, CGC SHEARWATER (SPEED 28 KTS)

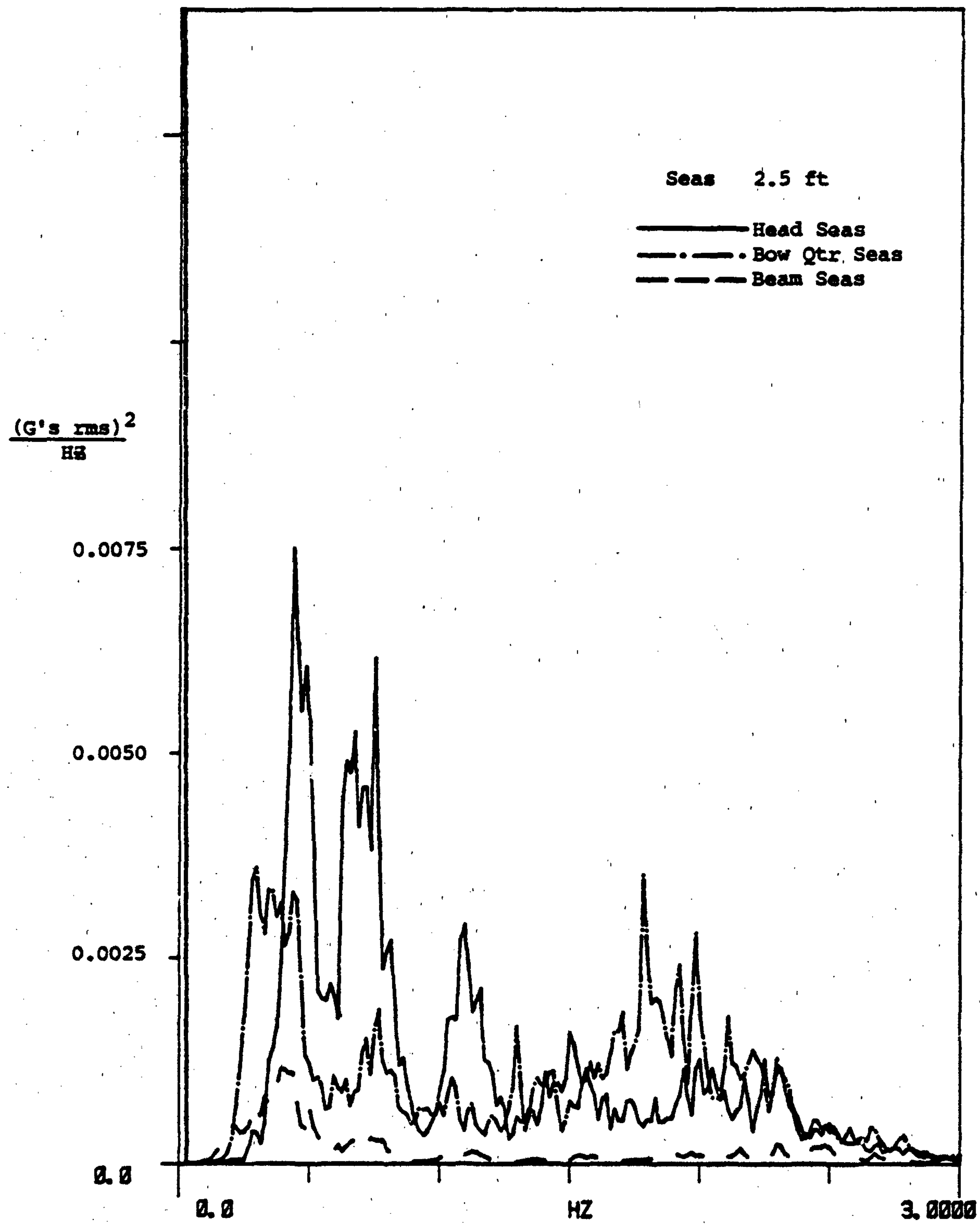
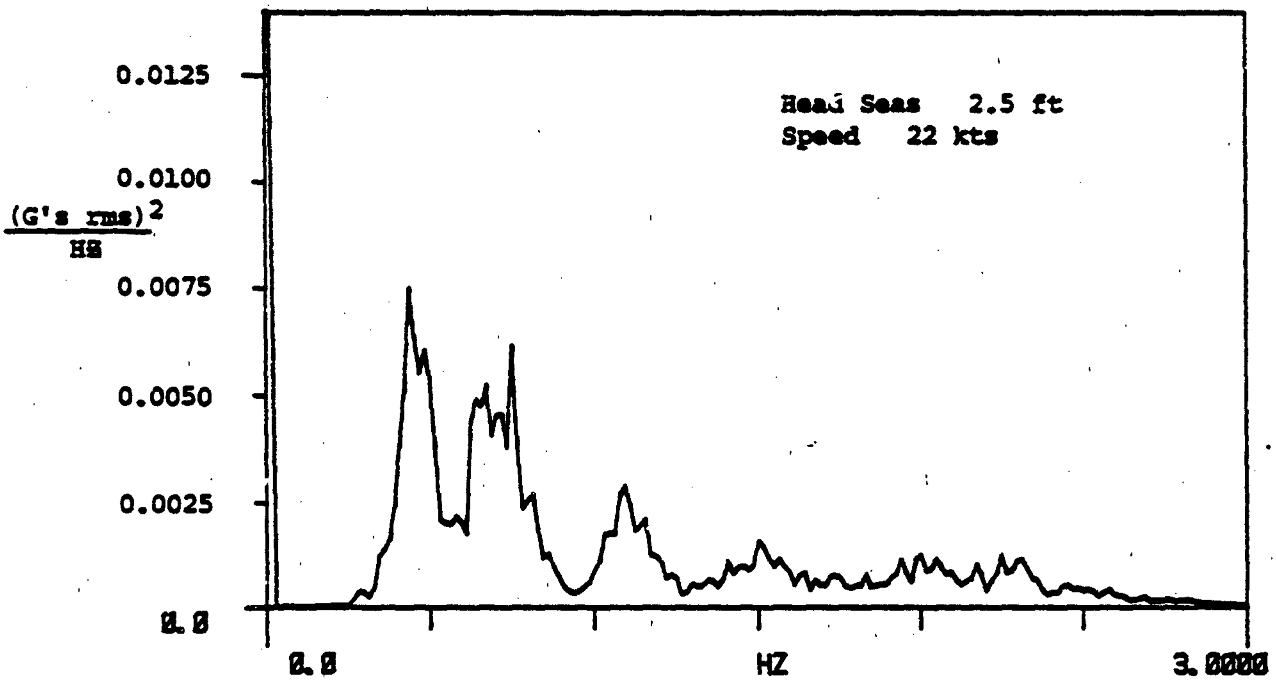


FIGURE 7. HEAVE PSD's, CGC SHEARWATER (SPEED 22 KTS)



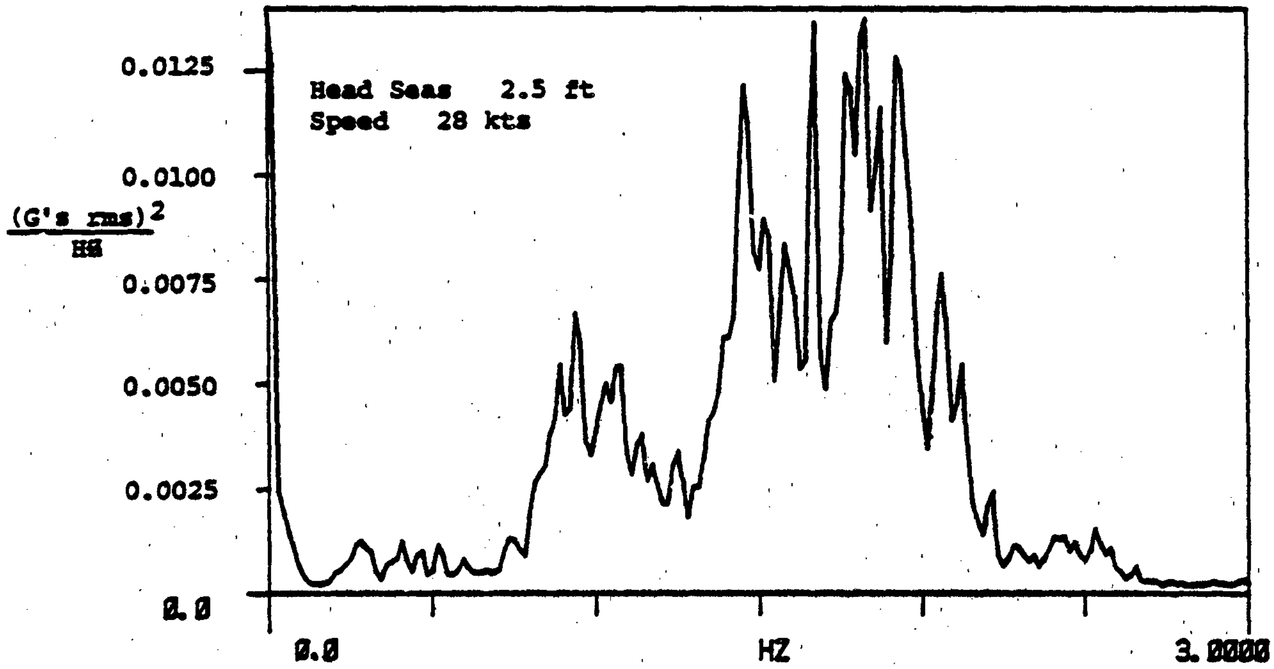


FIGURE 8. HEAVE PSD's, CGC SHEARWATER (HEAD SEAS, 22 AND 28 KTS)

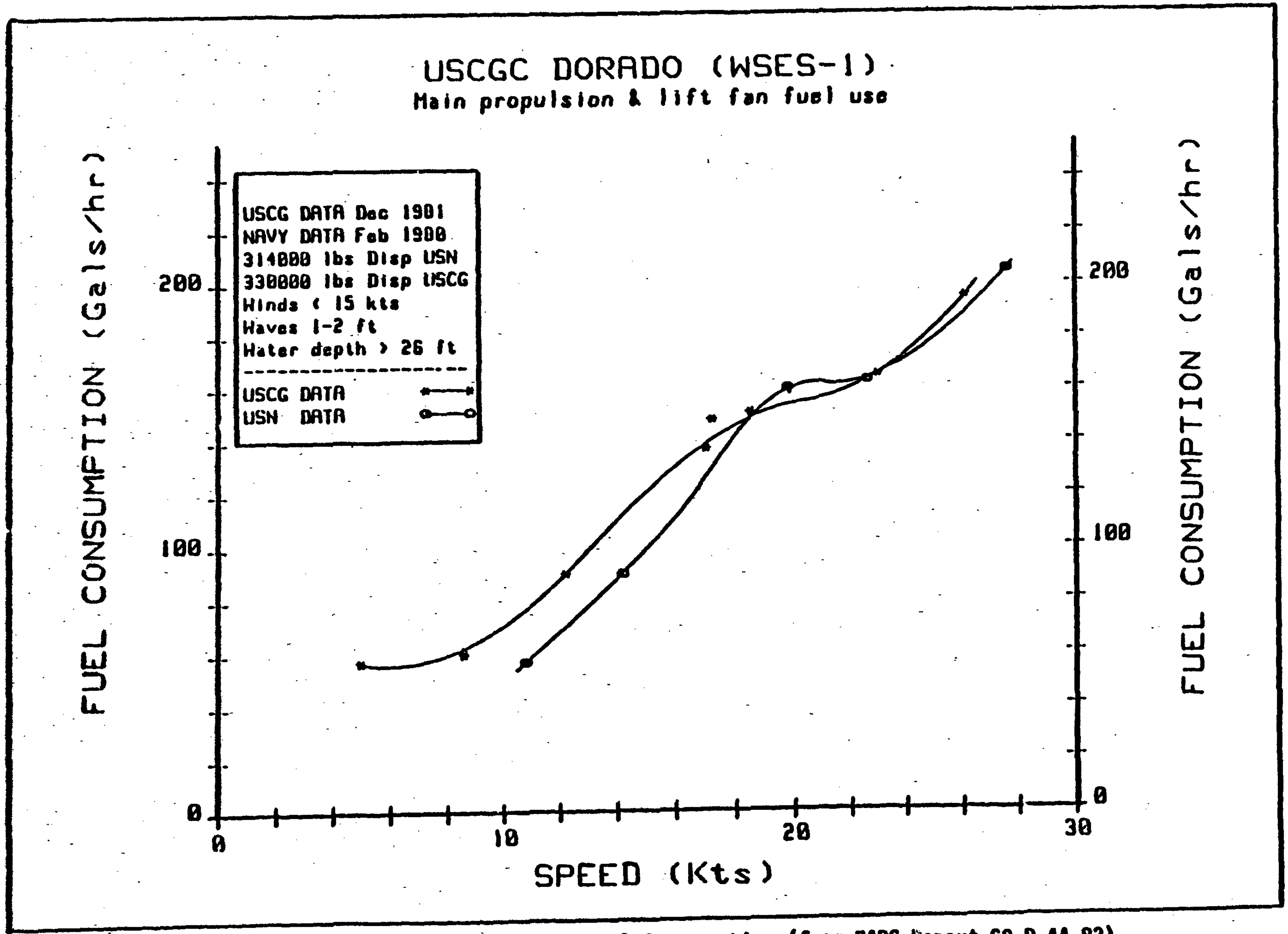


FIGURE 9. CGC DORADO Speed vs. Fuel Consumption (from R&DC Report CG-D-44-82)

Roll and pitch spectra were measured in order to determine if roll or pitch was strongly coupled to the high frequency heave power centered around 1.8 HZ at 28 knots. The roll and pitch spectra for head seas at 28 knots, Figures B17 and B18 show most of the energy centered at 0.23 HZ or 4.4 second period with a spike at 1.54 HZ.

The roll and pitch motion of the SHEARWATER are not strongly coupled to heave at the 1.8 HZ range. There is, however, a significant peak response in pitch caused by the natural heaving of the vessel which shows up in the pitch spectrum at 1.54 HZ.

That relatively high frequency vertical motion is related to the air cushion dynamics for this class vessel and is most pronounced at full speed 28 knots in head seas. In this head seas attitude the waves can travel down between the vessel side hulls virtually unobstructed. This situation may allow the waves to compress the air in the wet deck area and precipitate venting of the stern seal more readily than at other headings to the swells.

FATIGUE AND EXPOSURE LIMITS

The large amount of heave power at 1.8 HZ is a concern because motions in the range of 1 to 80 HZ cause human fatigue and eventual loss of proficiency over a period of time. These higher frequency motions are not usually encountered on conventional displacement craft. The heave motions aboard the SHEARWATER and SEA HAWK are within this range and merit more study considering possible degradation of crew performance and mission effectiveness related to human fatigue.

The four factors responsible for determining the human response to vibration are intensity, frequency, direction (vertical or horizontal) and duration (exposure time) of the vibration. The three quantifiable human responses to vibrations are the preservation of work efficiency, health or safety and comfort. In general, higher levels of vibration are acceptable when health and safety is the limiting criterion in comparison with working efficiency limits, reference (a).

The fatigue-decreased proficiency boundary, Figure 10, specifies a limit beyond which exposure to vibrations can be regarded as carrying a significant risk of impaired working efficiency in many tasks, especially time dependent tasks such as watch standing. Although individuals may respond differently to vibrations, the fatigue limits show the general level of onset of such degradation.

The sensitivity range for human reaction to fatigue type vibrations is 1 to 80 HZ. The most sensitive frequency ranges are 4 HZ to 8 HZ for vertical accelerations as seen by the horizontal portion of the fatigue limits in Figure 10 and 1-2 HZ for horizontal vibrations, reference (a).

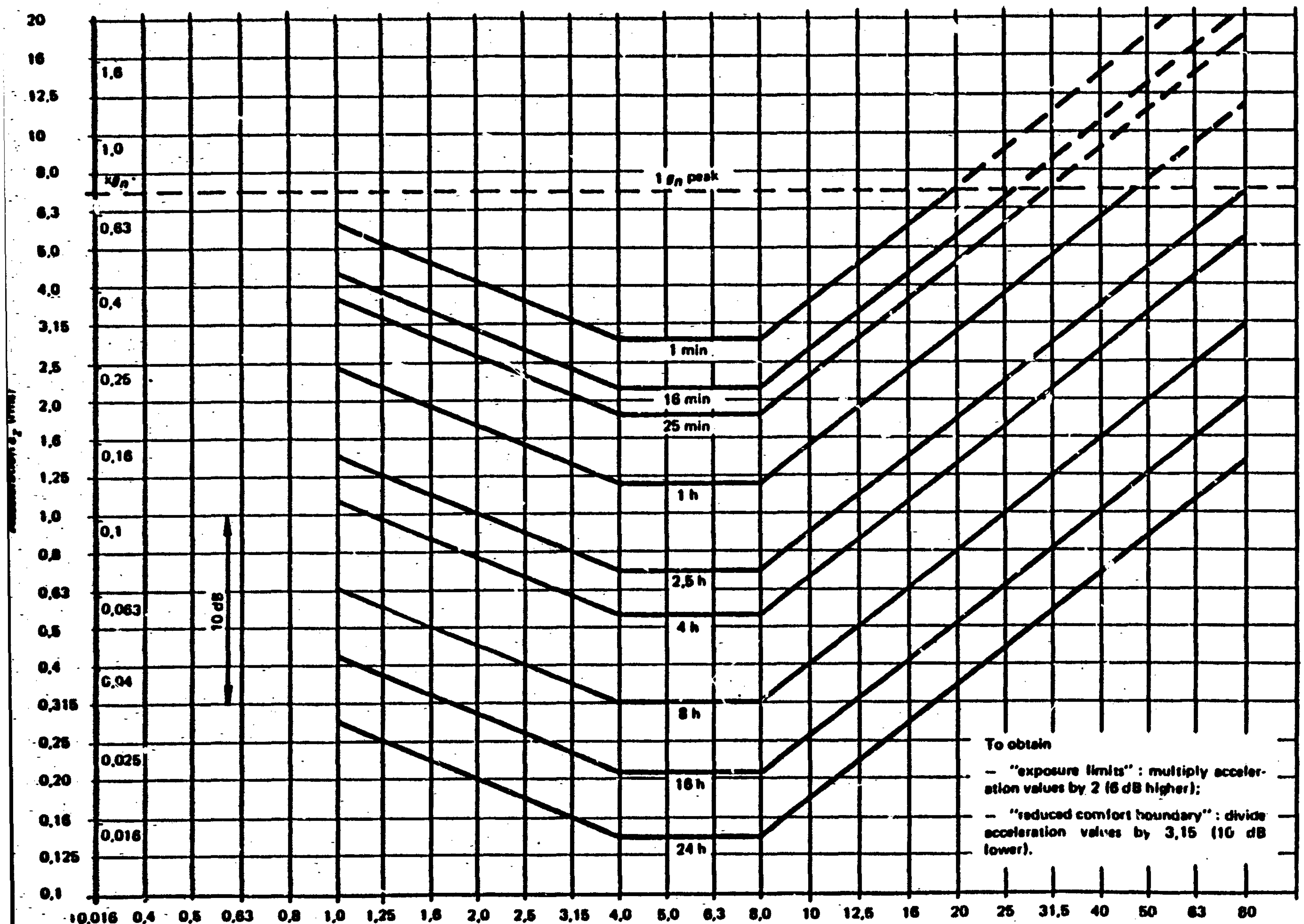


FIGURE 10. Longitudinal (a_z) acceleration limits as a function of frequency and exposure time; "fatigue — decreased proficiency boundary"

From ref. (a)

The exposure limit for health or safety is the same as the fatigue-decreased proficiency boundary but corresponding to acceleration levels two times higher (6 dB higher). The exposure limit is set at half the level considered to be the threshold of pain (or limit of voluntary tolerance) for a healthy male human subject restrained to a vibrating seat. According to the Air Force guidelines, reference (b), "For special military requirements these limits can be increased by a factor of 2. Such limiting levels have been explored in laboratory research."

Fatigue and exposure limits of vertical accelerations were computed for the CGC SHEARWATER and CGC SEA HAWK. The most severe case of the SHEARWATER underway in 2.5 foot head seas at 28 knots was taken as well as bow quarter and beam seas. The analysis assumes a constant exposure to these vertical accelerations depicted in the power spectrum density plots, Figures B1-B3. A one third octave band analysis was computed from these vertical acceleration narrow band spectra. Details of this procedure are outlined in Appendix C.

The results of this analysis as seen in Figure 11 show that the most sensitive 1/3 octave band centered at 2 HZ defines a Fatigue Decreased Proficiency (FDP) lower limit of 6 hours at 28 knots in head seas. The tabular data is presented in Appendix C, Table C2. The minimum time for reaching the exposure limit is obtained by reading the hours of exposure off the limit curves after dividing the plotted values by 2. In this case at 2 HZ corresponds to a 0.569 G's rms vertical acceleration. Half of that value (0.0285) on the graph in Figure 11 corresponds to a 19 hour exposure limit.

The CGC SEA HAWK fatigue limits are also analyzed using this technique. The analysis assumes a constant exposure to the vertical accelerations depicted in the PSD plot, Figure B19. The FDP limit for the most sensitive 1/3 octave band again 2.0 HZ is about 7 hours while proceeding at 17 knots in head seas 3-4 feet high, Figure 12. The tabular data is presented in Table C3 of Appendix C. The exposure limit is reached after 21 hours. The SEA HAWK and SHEARWATER limits are very close for head sea conditions considering they were in different sea states and proceeding at different speeds. As seen in Figure B20 the heave spectra for both vessels between 1-3 HZ are very similar.

These limit values on the SEA HAWK determined from 1/3 octave band analysis are now compared to the preferred weighted network approach according to reference (a) ISO standards. The Bruel & Kjaer Human Response Meter analyzed the same ship motions over the same time period, however, significantly shorter FDP and exposure limits were obtained. As outlined in Table II during 3-4 feet head seas, runs at 17 knots, the FDP limit was exceeded after 2.8 hours while the exposure limit was computed to be 7 hours. A bow quarter seas run resulted in a 3.8 hour FDP limit and 11.2 hour exposure limit in the same sea state.

Tasks requiring concentration and of a particularly demanding perceptual nature will begin to degrade at the end of FDP limits. This would include navigation, log keeping, steering, radar use, OOD, and lookout activities.

The effectiveness of the crew's ability to perform required tasks will degrade with increased vibration exposure. Safety and health considerations eventually become a factor when the exposure limit is reached.

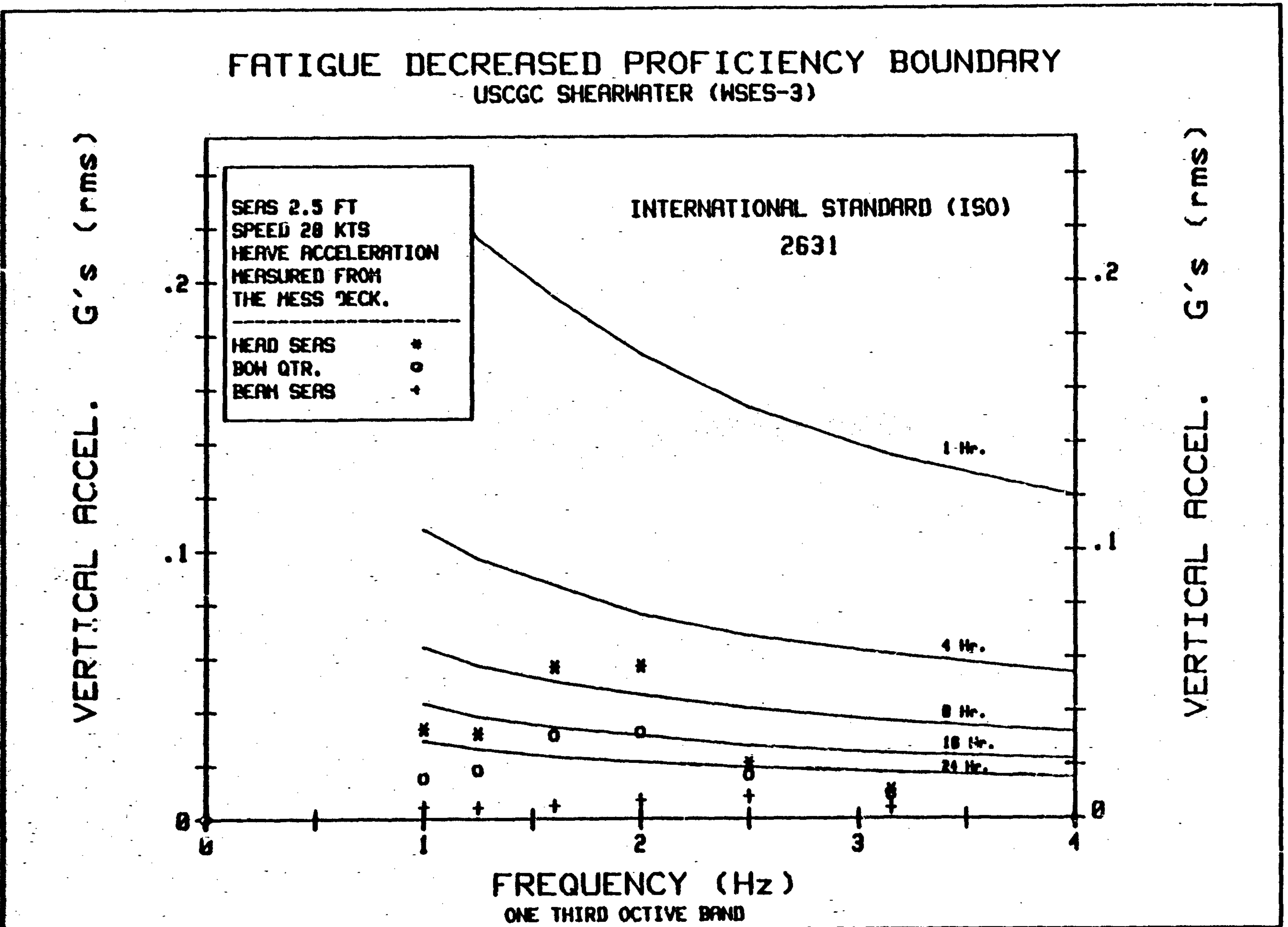


Figure 11. CGC SHEARWATER HEAVE 1/3 OCTIVE BAND ANALYSIS

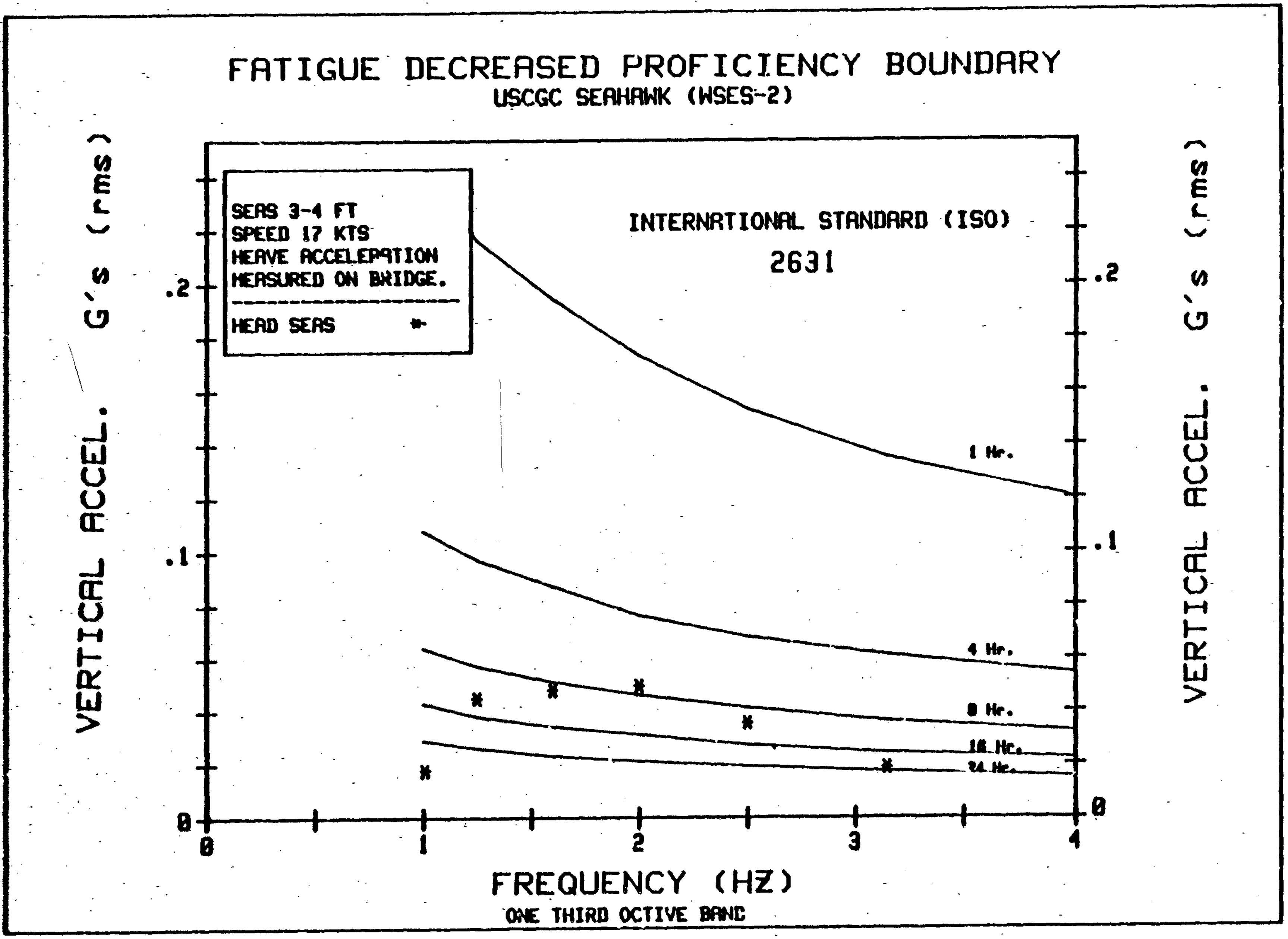


Figure 12. CGC SEA HAWK, HEAVE 1/3 OCTIVE BAND ANALYSIS

TABLE II

Summary of Human Response Vibration Meter* Measurements on CGC SEA HAWK

DATE	DISPLACMENT LONG TONS	SPEED KTS	SEA STATE	VESSEL HEADING	TIME TO REACH 100% FATIGUE DECREASED PROFICIENCY LIMIT (HOURS)	TIME TO REACH 100% EXPOSURE LIMIT (HOURS)	AVERAGE VERTICAL ACCEL. (WEIGHTED) (G's)
24 NOV 83	144 LT	8-10	1-2 FT Chop	Various	11.2 HR	28 HR	0.0234
25 NOV 83	130 LT	17	3-4 FT	Head Seas	2.8 HR	7.0 HR	0.0642
25 NOV 83	130 LT	17	3-4 FT	Bow Qtr Seas	3.8 HR	11.2 HR	0.0510
25 NOV 83	130 LT	21	3-4 FT	Following Seas	9.7 HR	27 HR	0.0229
7 AUG 84	142 LT	13	Calm	Various	6.8 HR	10.3 HR	0.0410
9 AUG 84	134 LT	18-23	1-2 FT Swell	Various(Stops)	3.0 HR	8.0 HR	0.0500
10 AUG 84	148 LT	18-20	1 FT Swell	Various	3.5 HR	8.7 HR	0.0730
				AVERAGE	5.8 HR	15.1 HR	

* Bruel & Kjaer Type 2512 Human Response Vibration Meter Utilized
Whole Body 1-80 HZ Range Z Axis. (Vertical) Accelerations Measured On the Bridge

SUMMARY

The 110' Coast Guard surface effect ships have excellent roll and pitch stability. The roll and pitch motions were not responsive to ship heading relative to the swells in 2.5' seas.

Severe vertical accelerations (0.32-0.40 G's average highest 1/3 single amplitude) were measured aboard the CGC SHEARWATER and CGC SEA HAWK in 2-4 ft head seas. The frequency of these whole body vertical accelerations are relatively high, around two cycles per second, the natural frequency of a flexed knee, reference (c) and most severe at head seas above 25 kts. These motions made walking difficult and, according to ISO standards, can cause decreased proficiency of crew members.

The average of seven tests conducted on the SEA HAWK using the weighted network method resulted in an average fatigue decrease proficiency limit being reached after 5.8 hours and exposure limit being exceeded after 15.1 hours. Fatigue and exposure limits obtained using the 1/3 octave band method for the 3-4 ft head seas run of the SEA HAWK were 2.7 times longer than limits obtained using the Bruel & Kjaer Human Response Vibration Meter which utilizes a weighted network measurement technique.

CONCLUSIONS AND RECOMMENDATIONS

The fatiguing effects of high frequency vertical accelerations aboard the surface effect ships can be reduced in two ways. Crew effectiveness can be improved by the sprint and drift patrol method commonly used by the SES Division. This would give the body time to recover with several stop periods each day, providing the vessel comes off cushion. The ISO 2631 standard does not have quantitative guidelines concerning a recovery effect. When seas are 2 feet or greater, the most severe vertical accelerations can be reduced by avoiding head seas steaming if at all possible. This will substantially increase the time to reach crew fatigue and exposure limits.

Extensive testing on these vessels in 1-4 foot seas shows that fatigue decreased proficiency limits are generally exceeded after 12 hours and the exposure limit is reached within the first 24 hours of a patrol. These fatigue effects can be reduced as noted above, however, they cannot be eliminated. Tasks requiring concentration such as navigation, log keeping, steering, lookout, and OOD activities will begin to degrade when the fatigue limit is passed. Rotating watch standers more frequently than usual after the first day of a patrol may be effective in preserving task efficiency.

Safety and health considerations become a factor when the exposure limit is exceeded. The ISO vertical acceleration exposure limit is exceeded each time a patrol exceeds one day with three day patrols being the norm. These vessels have only been operational in the Coast Guard since 1982 and possible long term vibration effects on personnel over a 2-3 year tour are undefined. Consideration should be given to further investigate this potential health problem.

A ride control system similar to the one used by the Navy on their 160' SES should be seriously considered to improve ride quality of the 110' Coast Guard SES's. The venting of the air cushion pressure to reduce vertical accelerations may however cause a loss of overall cushion pressure making it even more difficult to attain full design speed considering the present difficulty SES's have in reaching full speed.

REFERENCES

(a) International Organization For Standardization (1978), "Guide For The Evaluation Of Human Exposure To Whole-Body Vibration", Ref. No.ISO 2631-1978(E)

(b) AFSC (1980), "Evaluation Of Human Exposure To Whole-Body Vibration", U.S. Air Force Publication, AFSC DH 1-3, SECT 3E, DN3E1, 25 June 80, pp. 3-13

(c) Bruel and Kjaer (1982), "Human Body Vibration", Technical Review No. 1, 1982 , Bruel & Kjaer Instruments, Inc., p.5.

APPENDIX A
SPECTRAL ANALYSIS EQUIPMENT AND PROCEDURES

Hewlett-Packard 5420A
Digital Signal Analyzer

This analyzer was utilized for various frequency domain measurements of ship motions utilizing an auto spectrum measurement. All ship motion records were analyzed and averaged over a 15-20 minute period to obtain a good statistically representative spectra in each case.

An analog signal is sampled through an analog low-pass filter to prevent aliasing. Aliasing is a phenomenon that can occur whenever a signal is not sampled at greater than twice its maximum frequency (the Nyquist rate). The analyzer's built-in anti-alias filters prevent aliasing error on all available measurement bandwidths. The measurement menu is set up by the user.

All spectral plots in this report were generated using an Auto Spectrum frequency domain measurement. An Auto Spectrum is the magnitude squared of the linear spectrum. The auto spectrum can be represented in three ways depending upon the signal type or (window) selected. Sinusoidal (P301), Random (Hanning) and Transient (rectangular) windows are available.

All heave spectra in this report are generated utilizing a random signal "Hanning" window which results in a Power Spectral Density (PSD) plot with units (G's rms)^2/HZ. This allows measurements made with different analysis ranges (bandwidths) comparable to one another. Roll and pitch spectra were measured using a sinusoidal (P301) window. These spectra have units, in this case, of Degrees rms. The correct amplitude value at any desired frequency can be read directly off the plot. Comparison of peak amplitudes for spectra generated in this way can be accomplished only when using the same analysis range (bandwidth).

An amplitude spike occurs on many of the spectral plots at a very low frequency below 0.05 HZ. This spike is caused by a DC drift in the sensor signal amplifier. It represents a very low frequency "noise" which should be ignored since it does not represent ship motion energy.

Power is computed in the frequency domain, either over its entire frequency measurement or over a band defined by the X-band cursors. This automatic computation was used to determine power in heave measurements. Power contained in 1/3 octave bands was computed when determining the human response to vertical accelerations on the SHEARWATER and SEA HAWK. Power units in this case are (G's rms)^2. This 1/3 octave band and weighting procedure is outlined in Appendix C. The power calculation was also applied to the heave spectra of the SHEARWATER to determine the amount of heave power shift from a 1 HZ bandwidth centered at 1.8 HZ during speed and heading changes of the vessel, Appendix B.

Set-up states for the spectral measurements were:

(1) For all heave PSD measurements:

Measurement:	Auto Spectrum
Average:	Stable; #A: (indicated number of averages)
Signal:	Random (uses "hanning" window)
Bandwidth:	4.0 HZ (only 3 HZ information is displayed on plot)
Time Length:	64 Sec.
	ΔF: 15.62 m HZ ΔT: 62.5 m Sec.
Calibration:	2.0 x volts = G's acceleration (for CGC SHEARWATER)
	0.645 x volts = G's acceleration (for CGC SEA HAWK)

(2) For all pitch and roll spectral measurements:

Measurement:	Auto Spectrum
Average:	Stable: #A: (indicating number of averages)
Signal:	Sinusoidal (P301 window)
Bandwidth:	2.0 HZ
Time Length:	128 Sec.
	ΔF: 7.812 m HZ ΔT: 125.0 m. Sec.
Calibration:	350.84 x volts = Degree Roll
	172.5 x volts = Degrees Pitch

Notations on Axis:	HZ -	Hertz (frequency)
	m -	Units x 10^{-3}
	μ -	Units x 10^{-6}
	#A -	Number of averages taken to generate the spectral plot
	X -	Location of left-most X axis cursor
	ΔX -	Bandwidth between two X axis cursors
	Power -	Area under the spectral plot between two X axis cursors (units rms)^2

APPENDIX B

MOTION SPECTRAL PLOTS

FOR

CGC SHEARWATER AND CGC SEA HAWK

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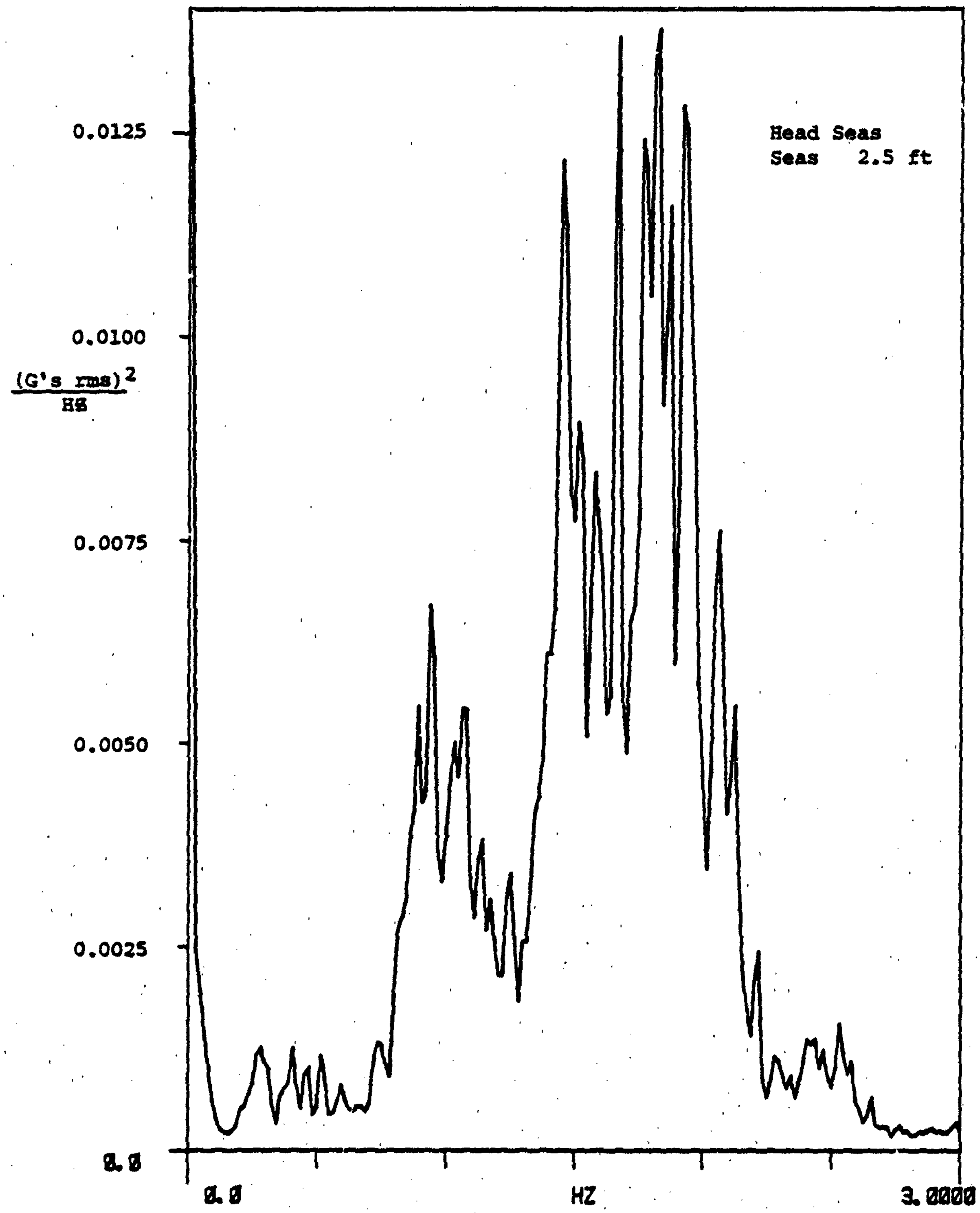

FIGURE B1. HEAVE PSD, CGC SHEARWATER (28 KTS HEAD SEAS)

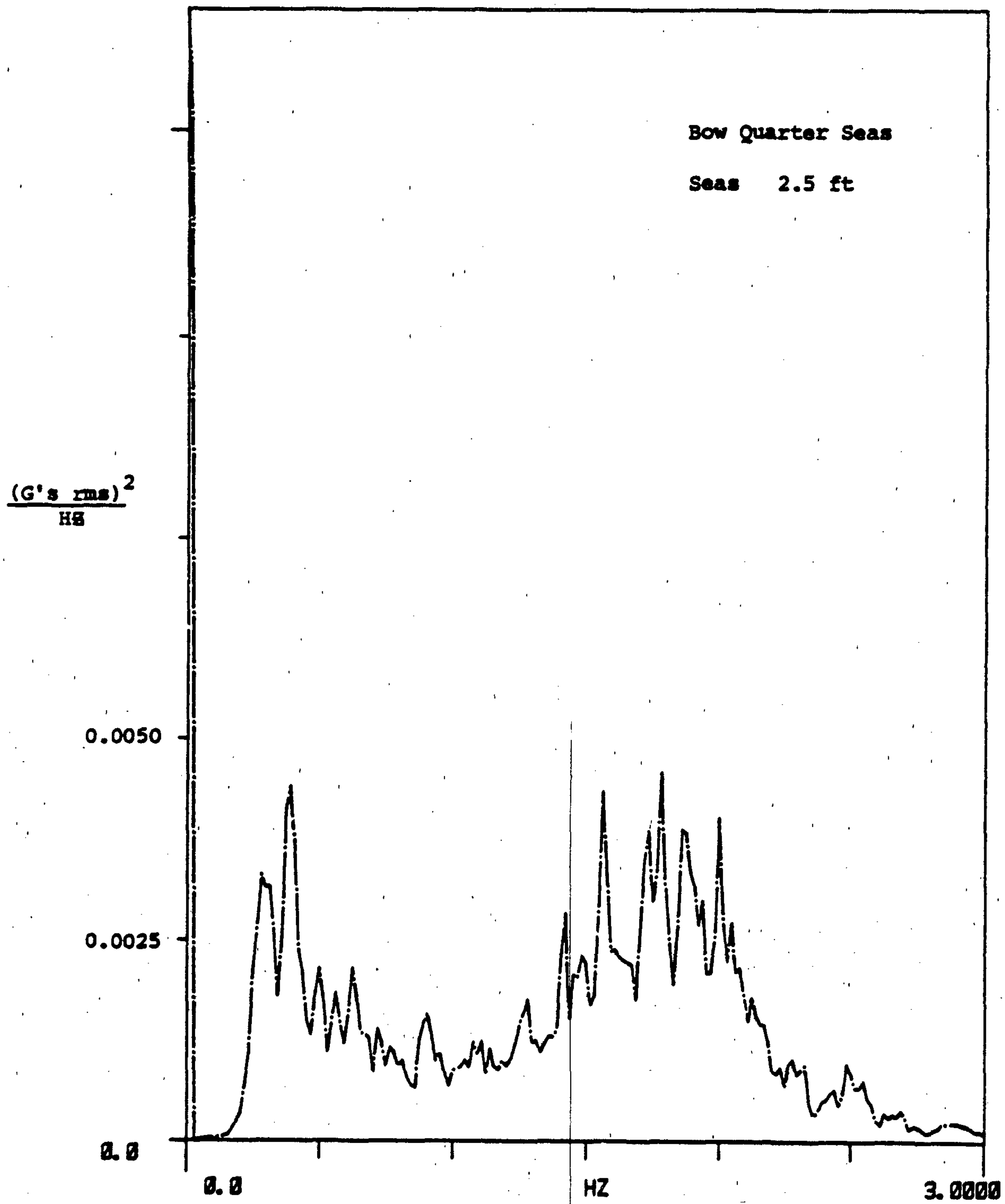

FIGURE B2. HEAVE PSD, CGC SHEARWATER (28 KTS BOW QTR SEAS)

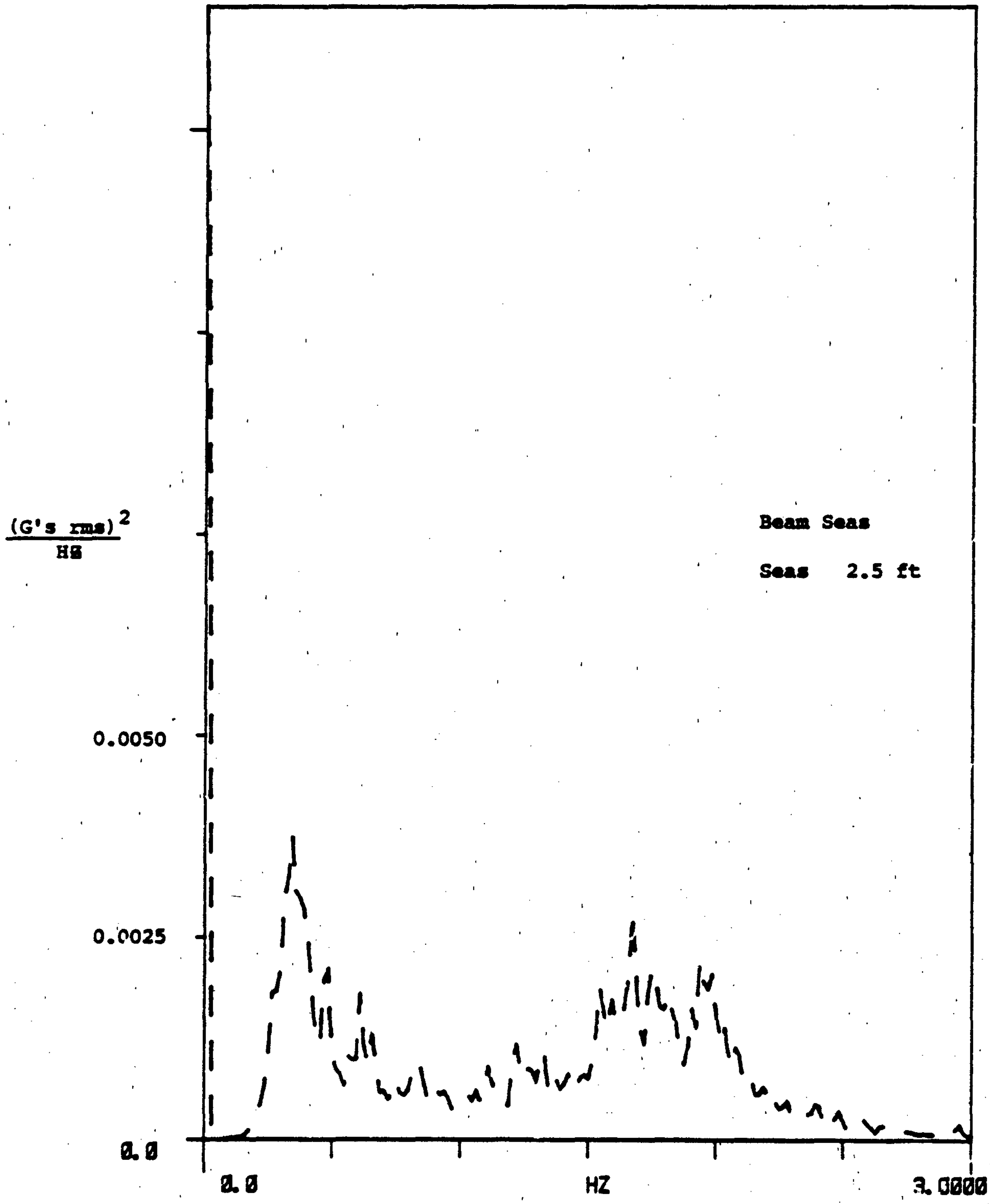

FIGURE B3. HEAVE PSD, CGC SHEARWATER (28 KT BEAM SEAS)

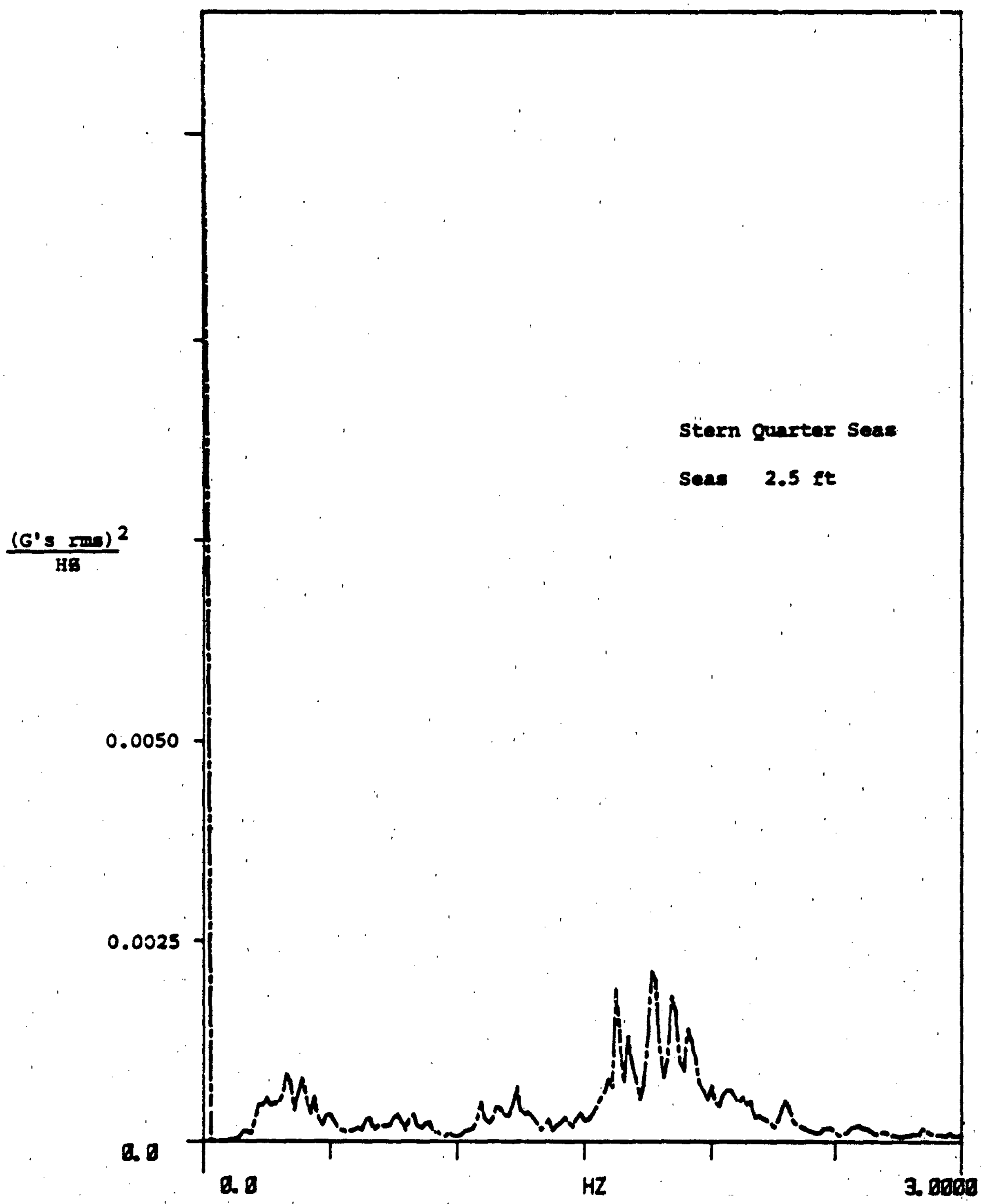

FIGURE B4. HEAVE PSD, CGC SHEARWATER (28 KTS, STERN QTR SEAS)

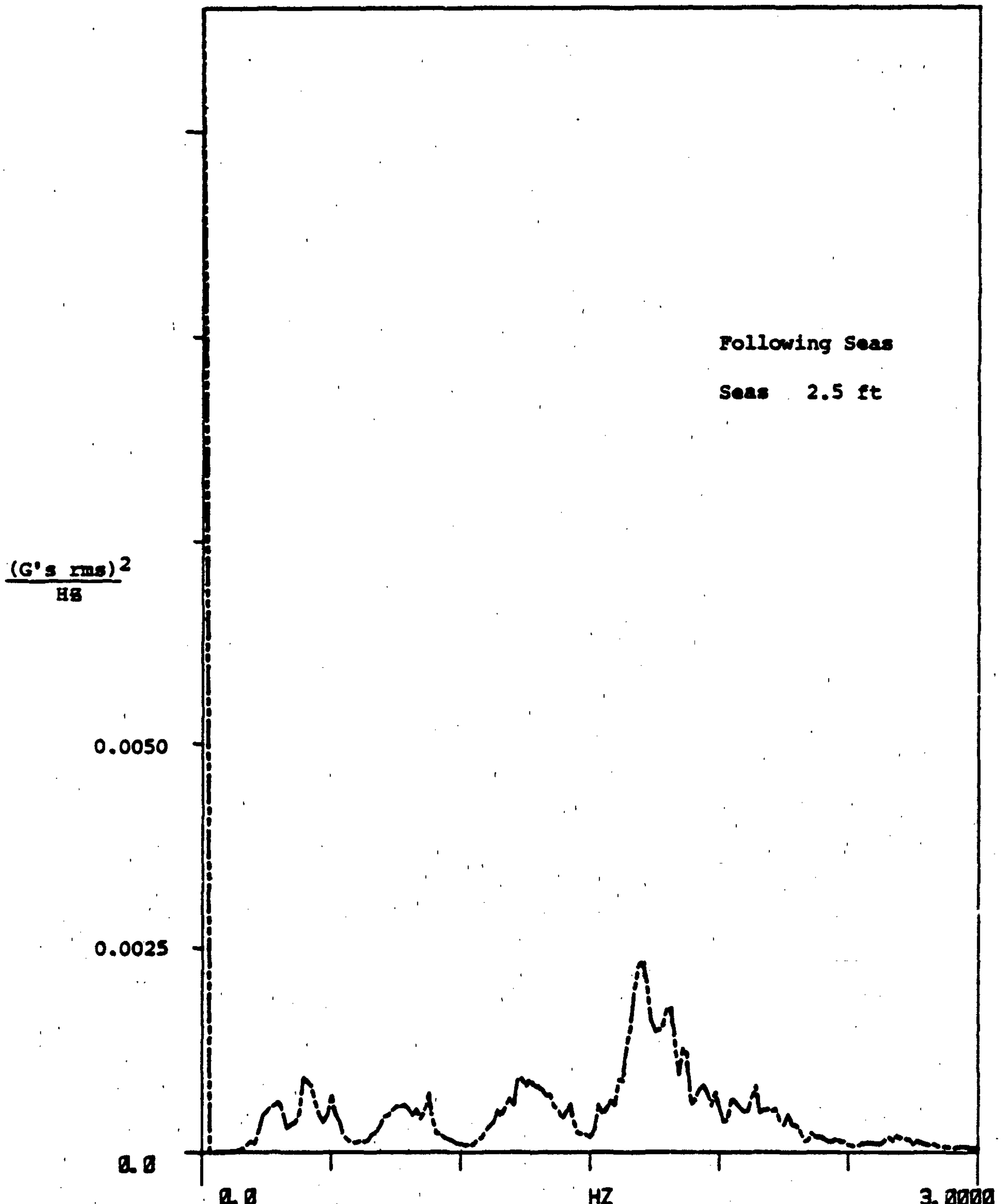

FIGURE B5. HEAVE PSD, CGC SHEARWATER (28 KTS FOLLOWING SEAS)

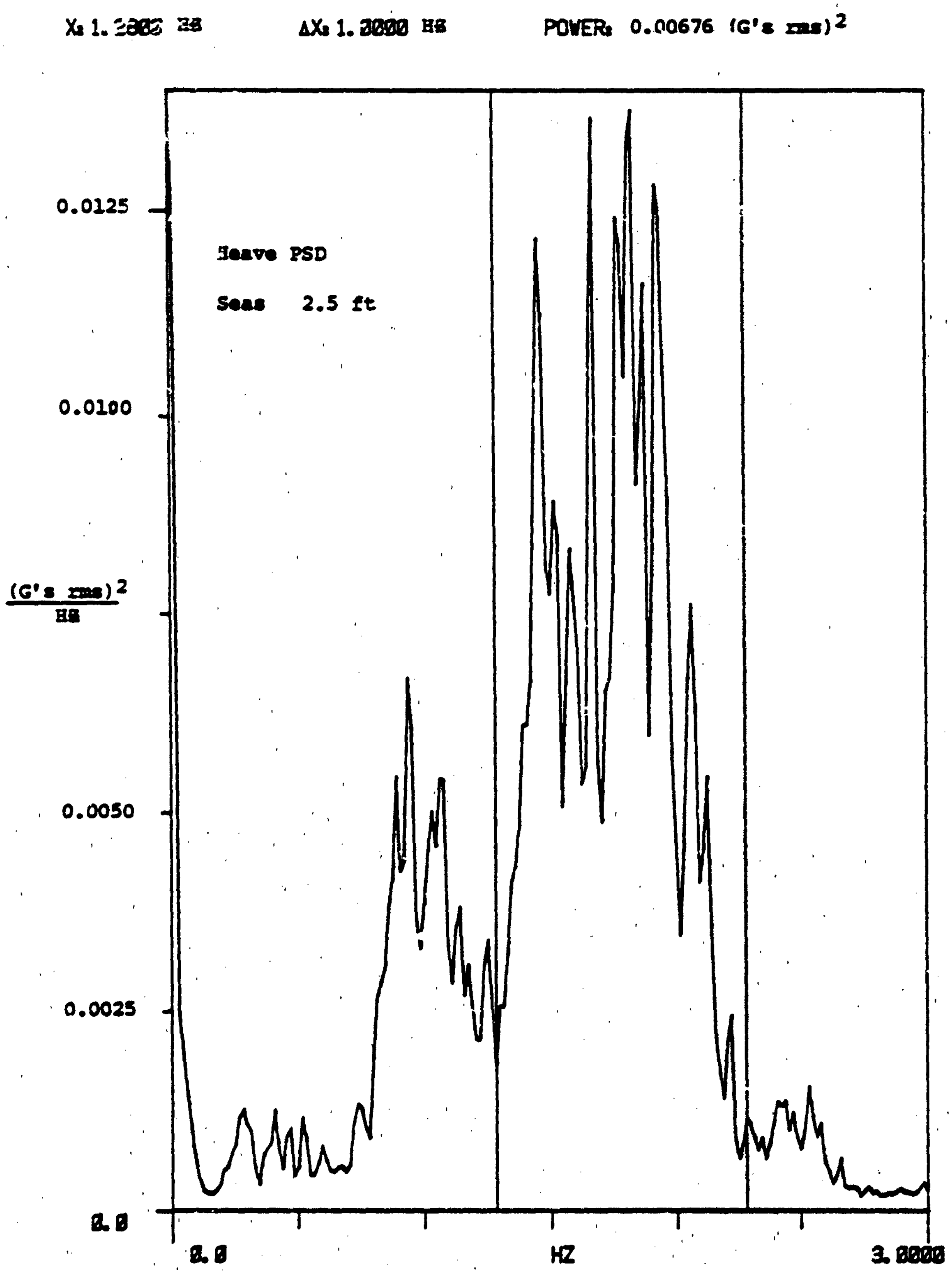

FIGURE B6. HEAVE POWER, CGC SHEARWATER (28 KTS HEAD SEAS)

X: 1.2800 HZ   ΔX: 1.0000 HZ   POWER: 0.00227 (G's rms)^2

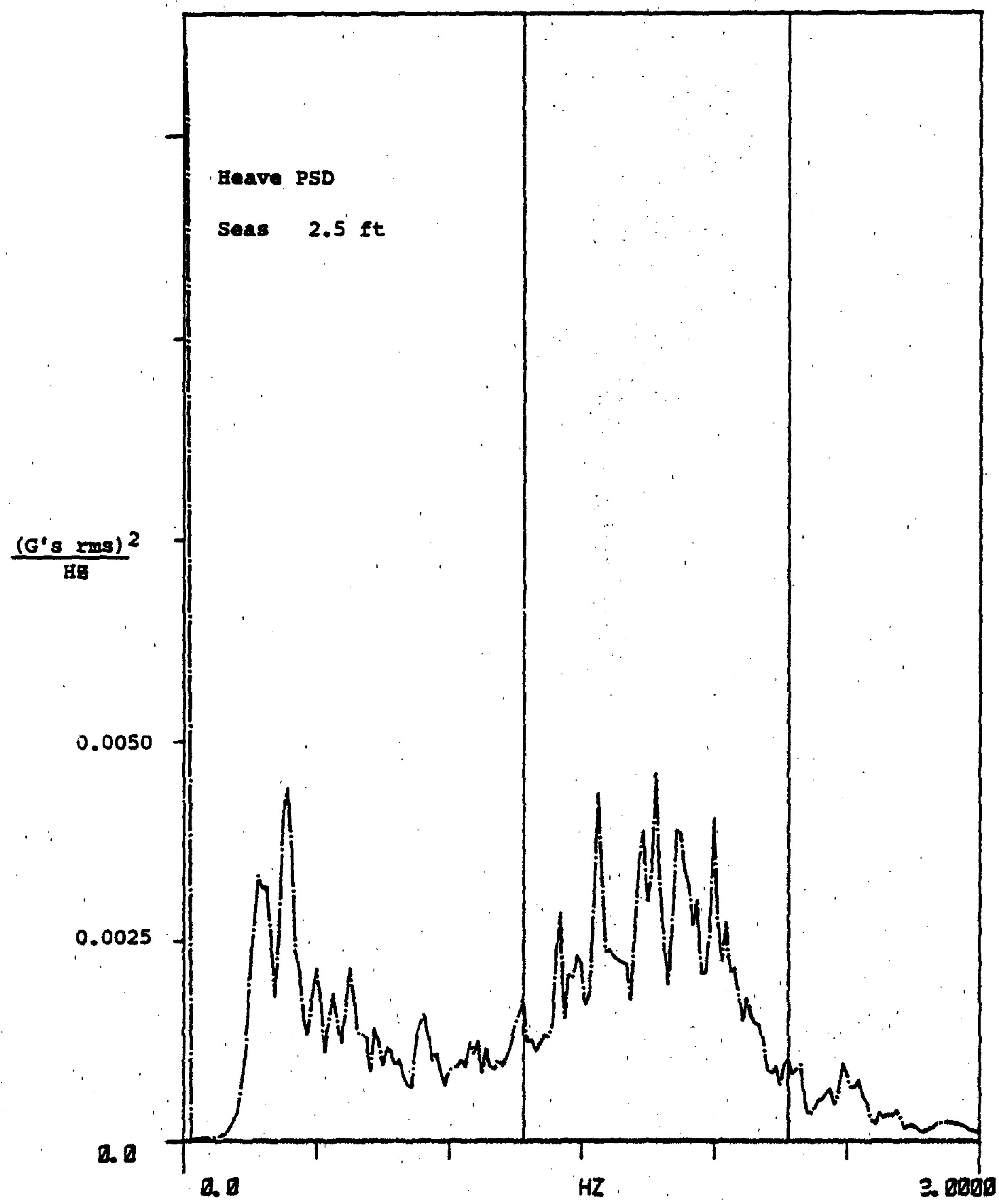

FIGURE B7. HEAVE POWER, CGC SHEARWATER (28 KTS BOW QTR SEAS)

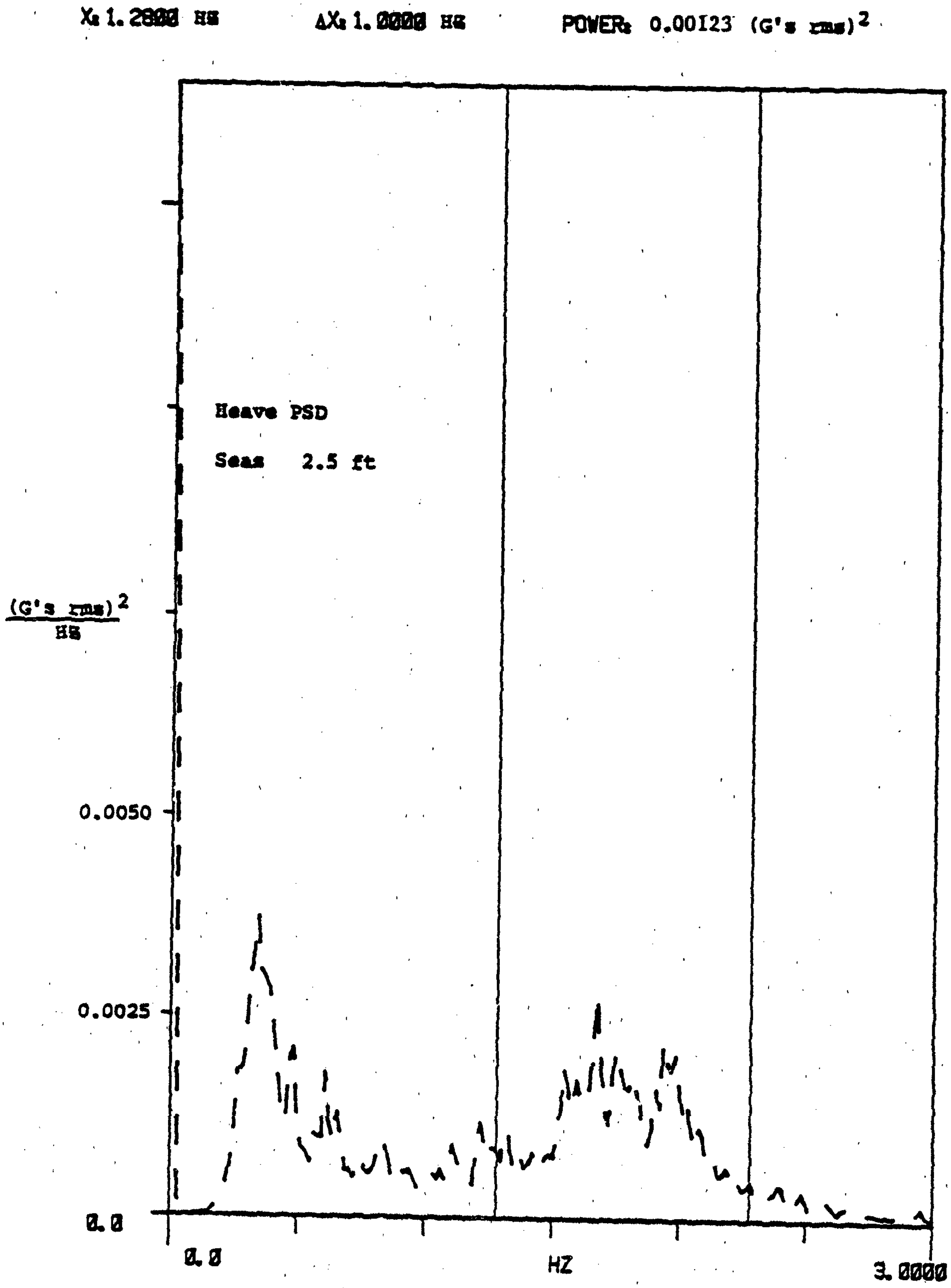

FIGURE B8. HEAVE POWER, CGC SHEARWATER (28 KTS BEAM SEAS)

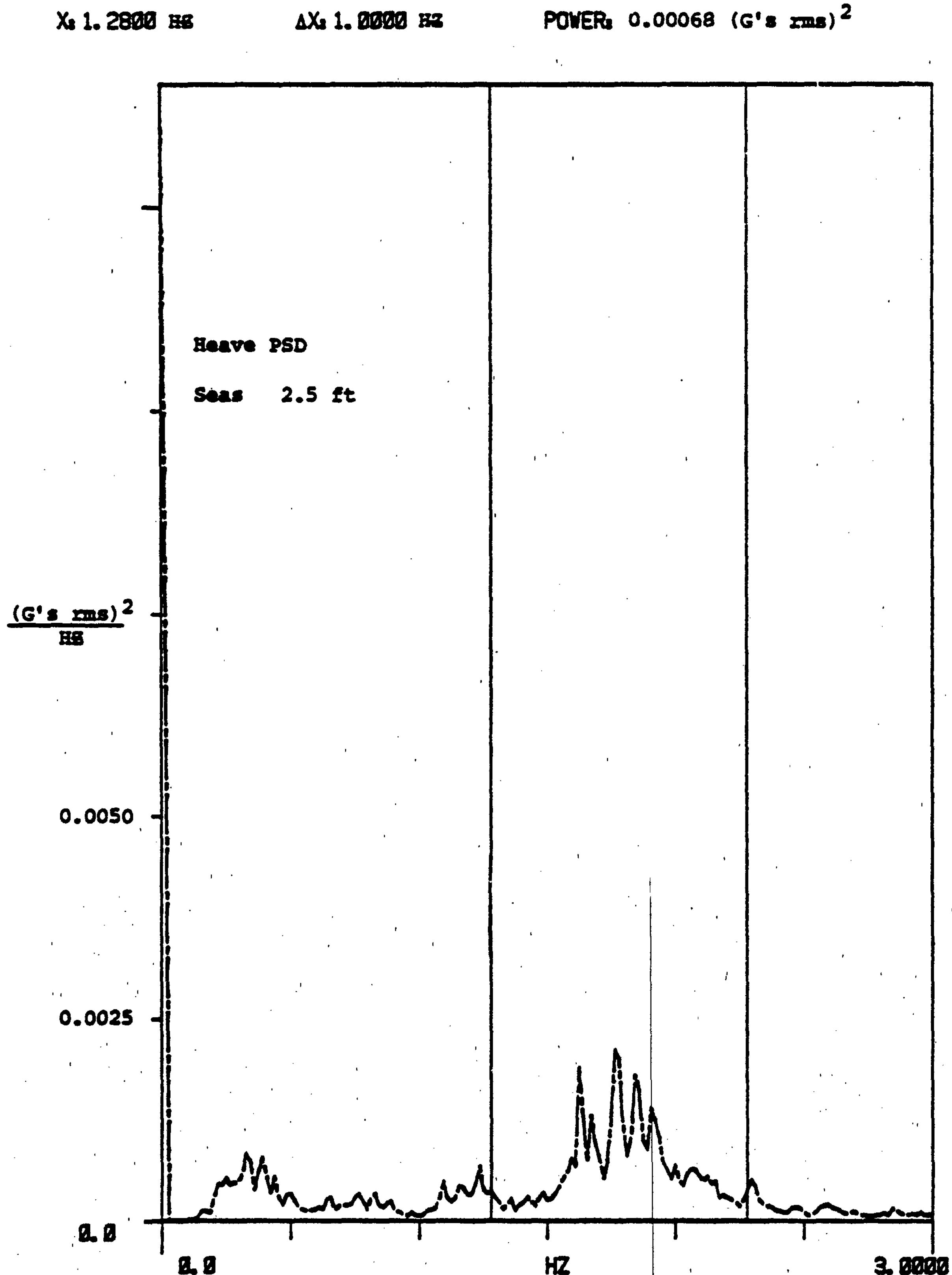

FIGURE B9. HEAVE POWER, CGC SHEARWATER (28 KTS, STERN QTR SEAS)

X: 1.2800 HZ ΔX: 1.0000 HZ POWER: 0.00083 (G's rms)^2

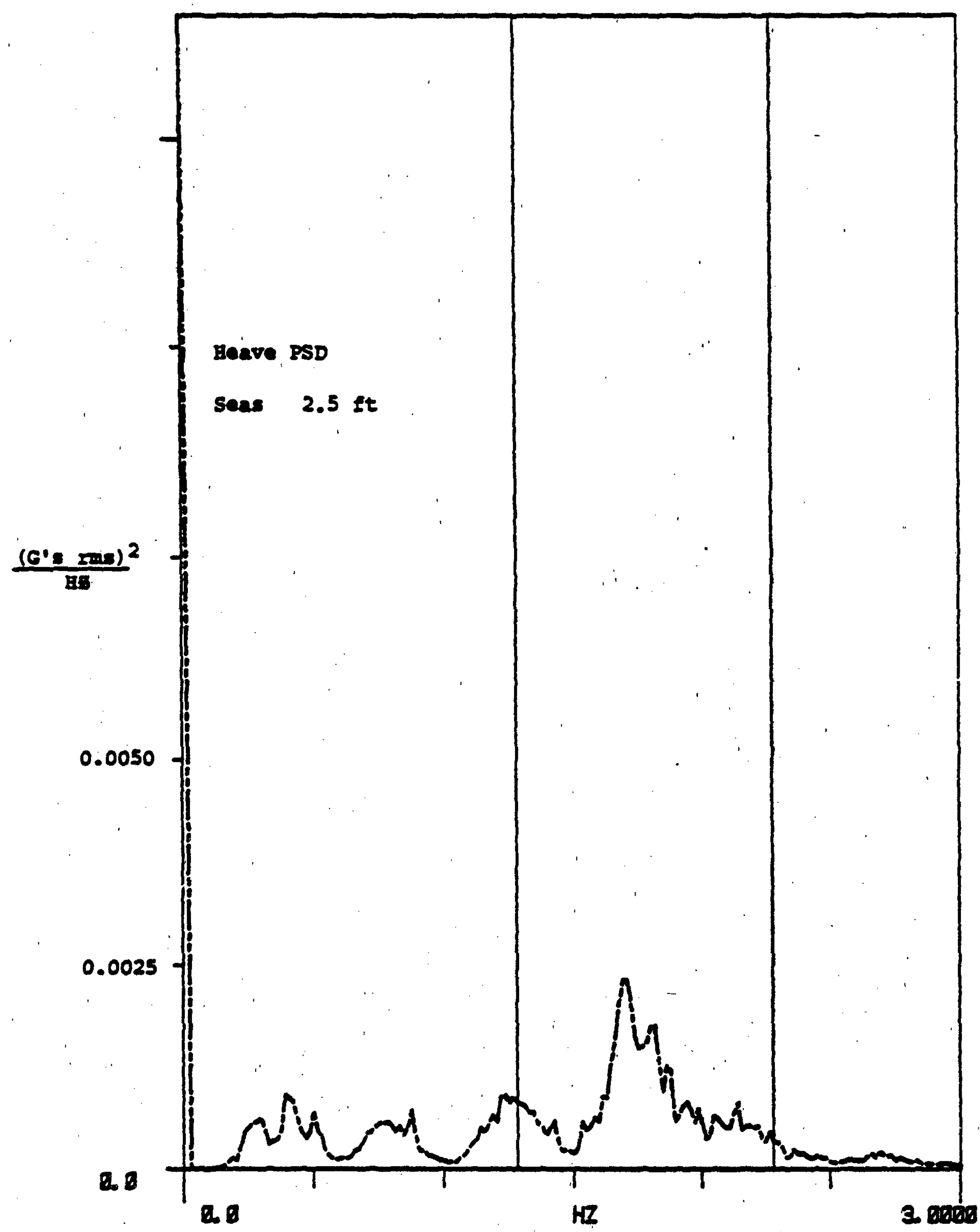

FIGURE B10. HEAVE POWER, CGC SHEARWATER (28 KTS FOLLOWING SEAS)

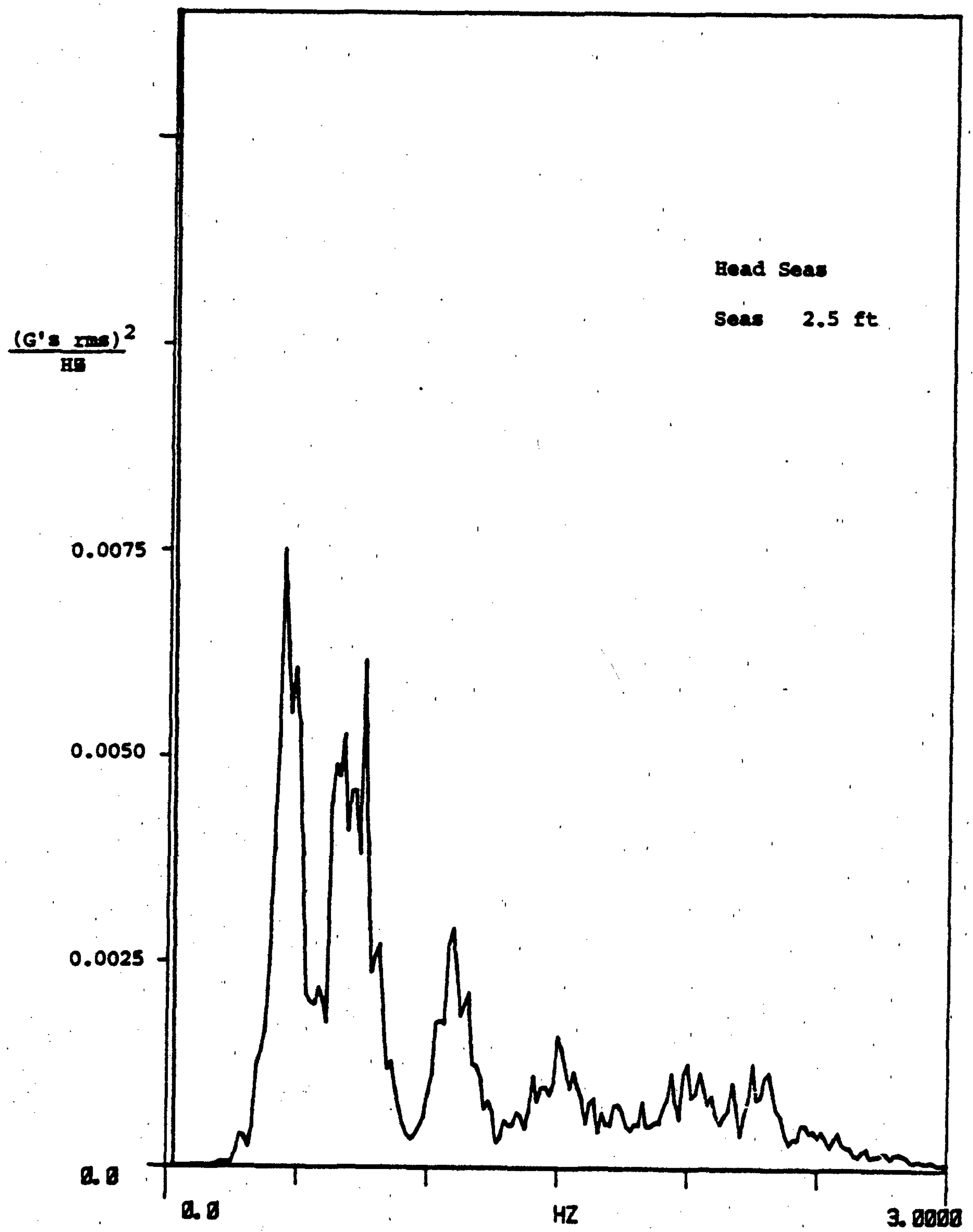

FIGURE B11. HEAVE PSD, CGC SHEARWATER (22 KTS HEAD SEAS)

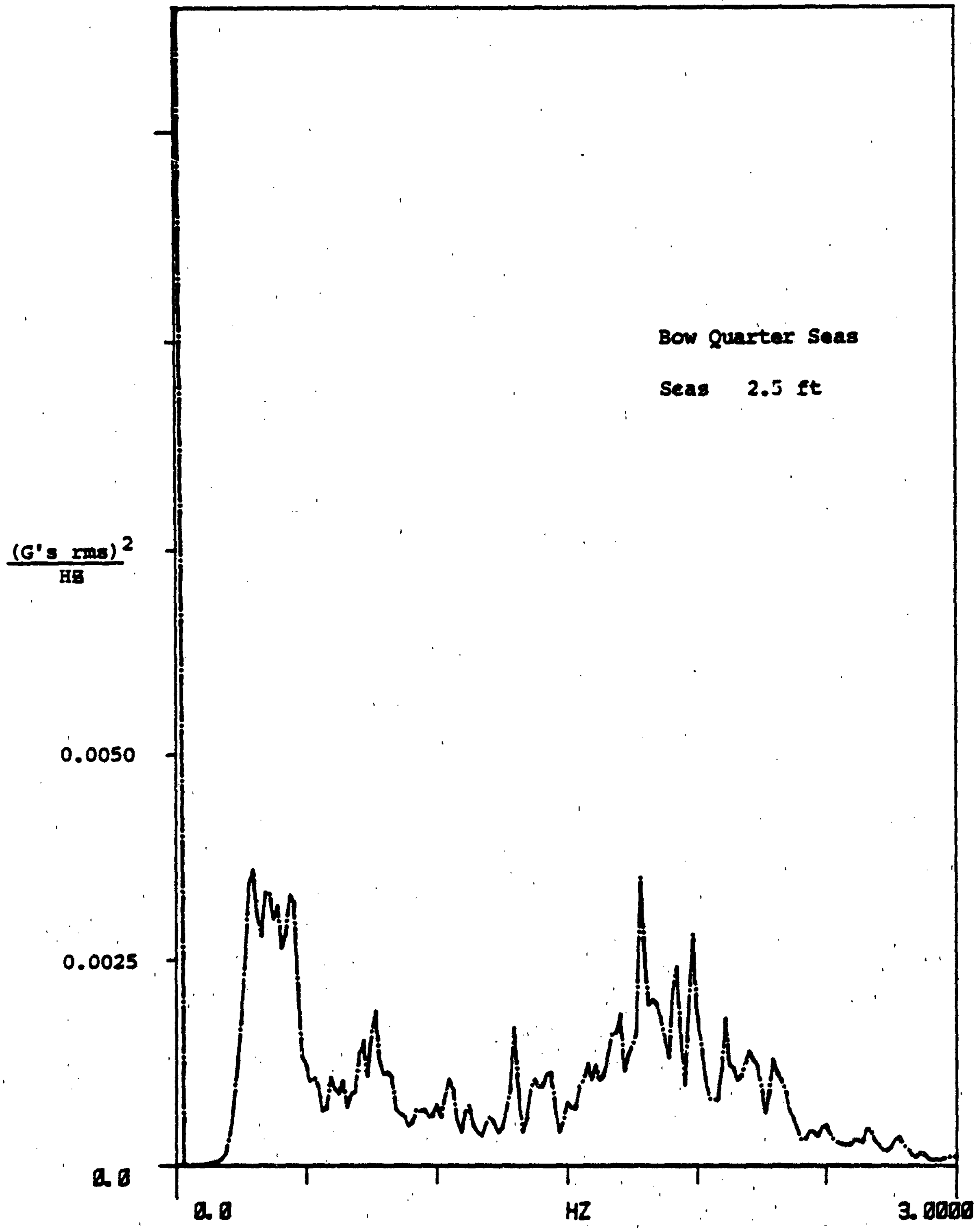

FIGURE B12. HEAVE PSD, CGC SHEARWATER (22 KTS BOW QTR SEAS)

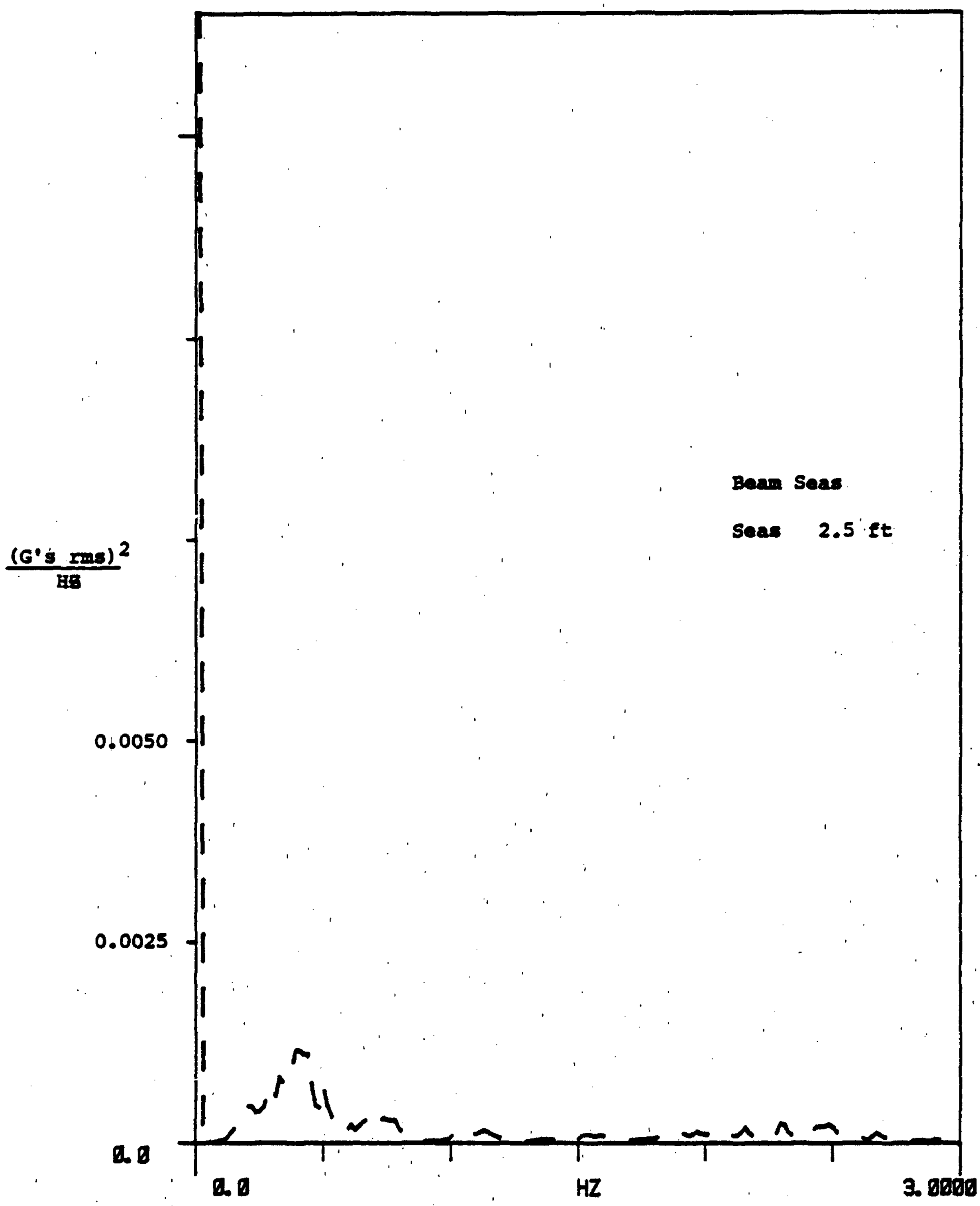

FIGURE B13. HEAVE PSD, CGC SHEARWATER (22 KTS BEAM SEAS)

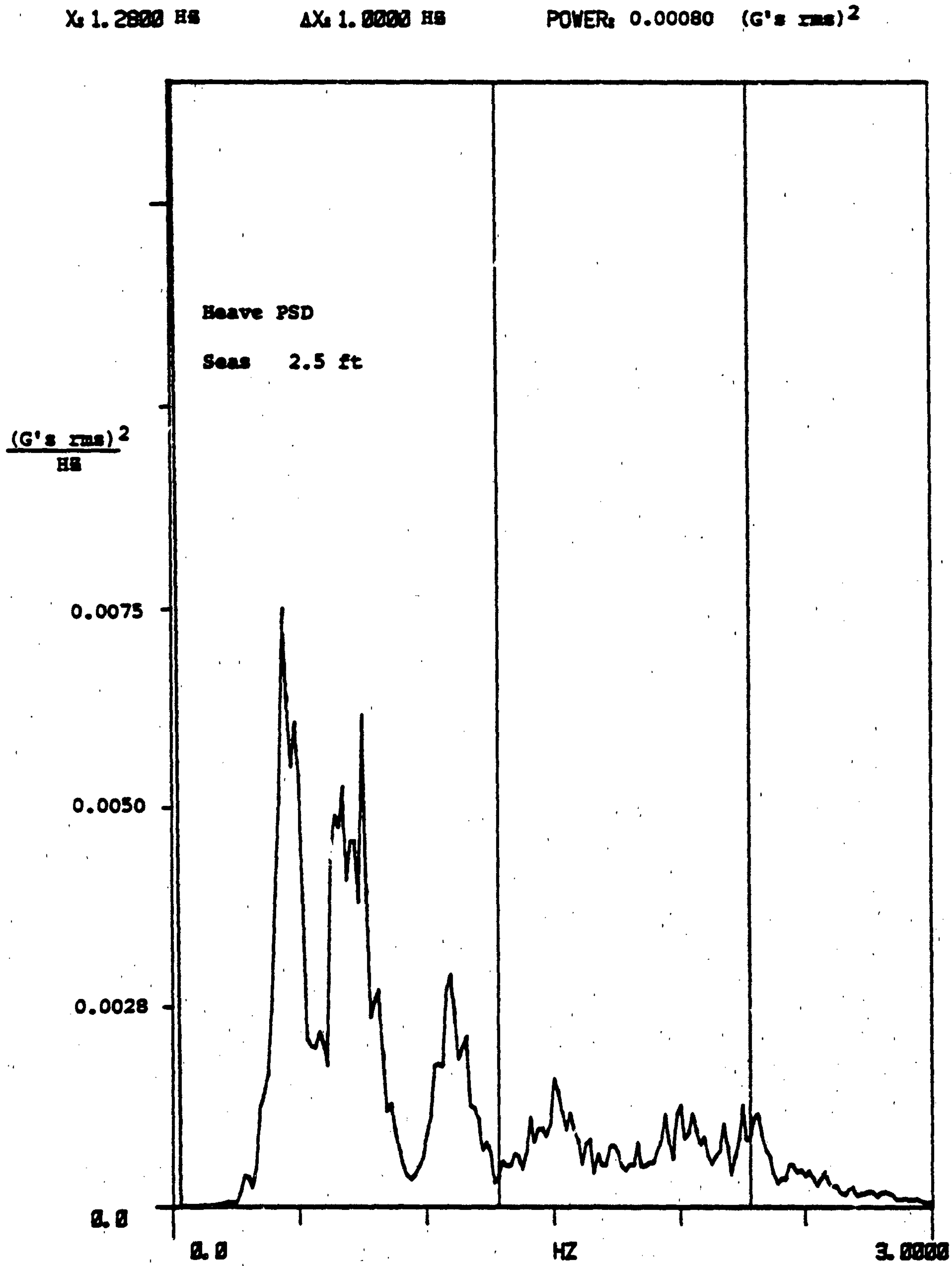

FIGURE B14. HEAVE POWER, CGC SHEARWATER (22 KTS HEAD SEAS)

X: 1.2800 HZ ΔX: 1.0000 HZ POWER: 0.00133 (G's rms)^2

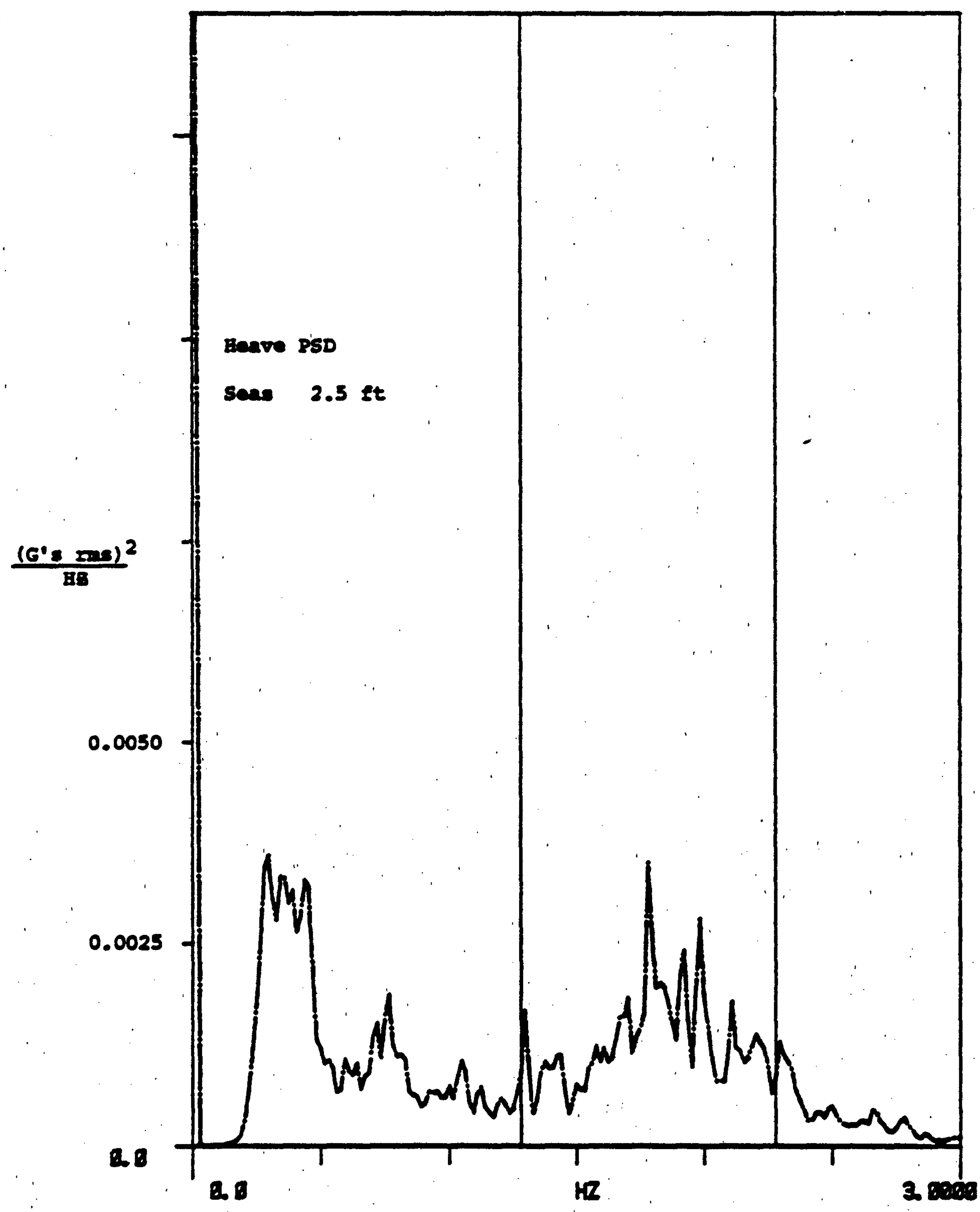

FIGURE B15. HEAVE POWER, CGC SHEARWATER (22 KTS BOW QTR SEAS)

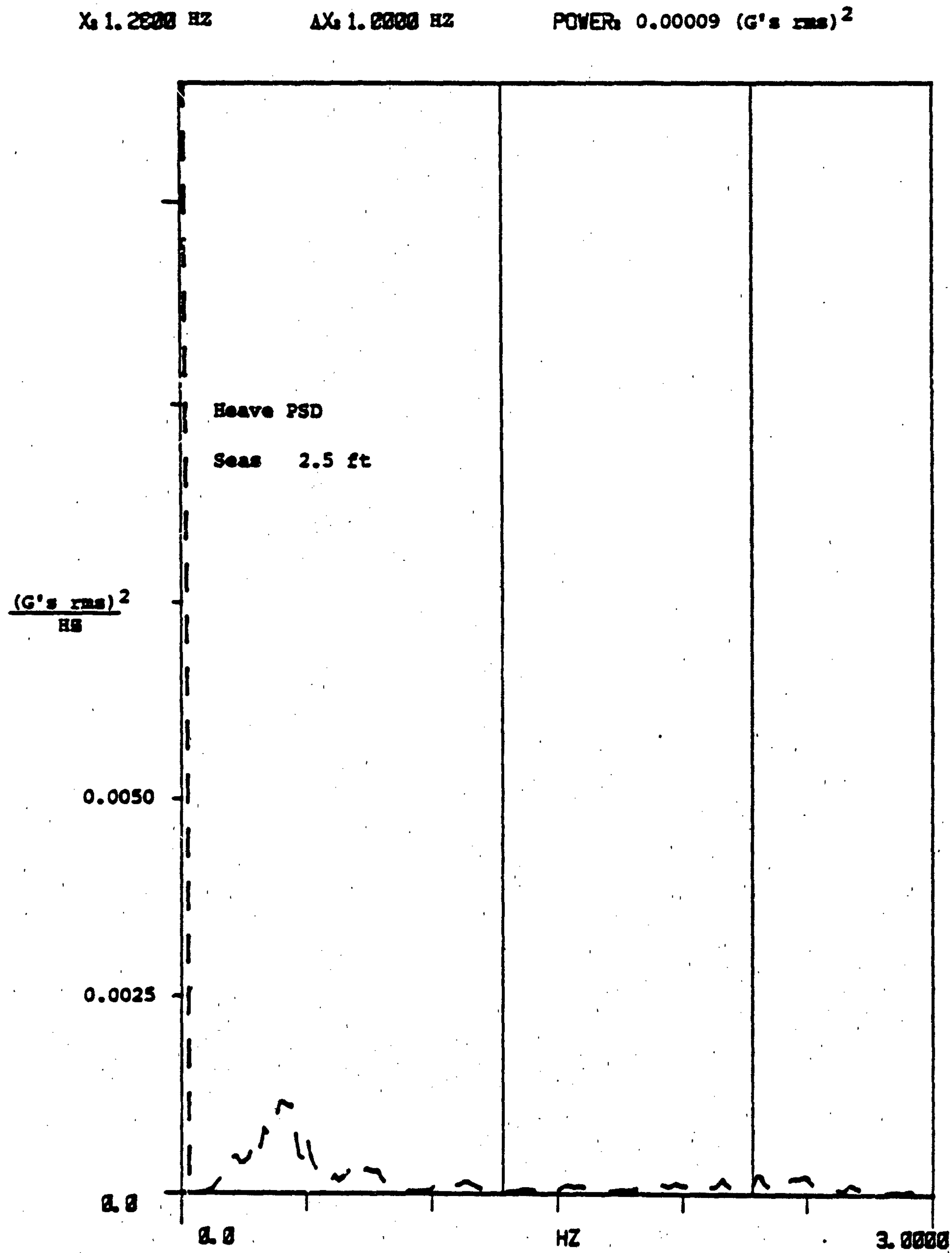

FIGURE B16. HEAVE POWER, CGC SHEARWATER (22 KTS BEAM SEAS)

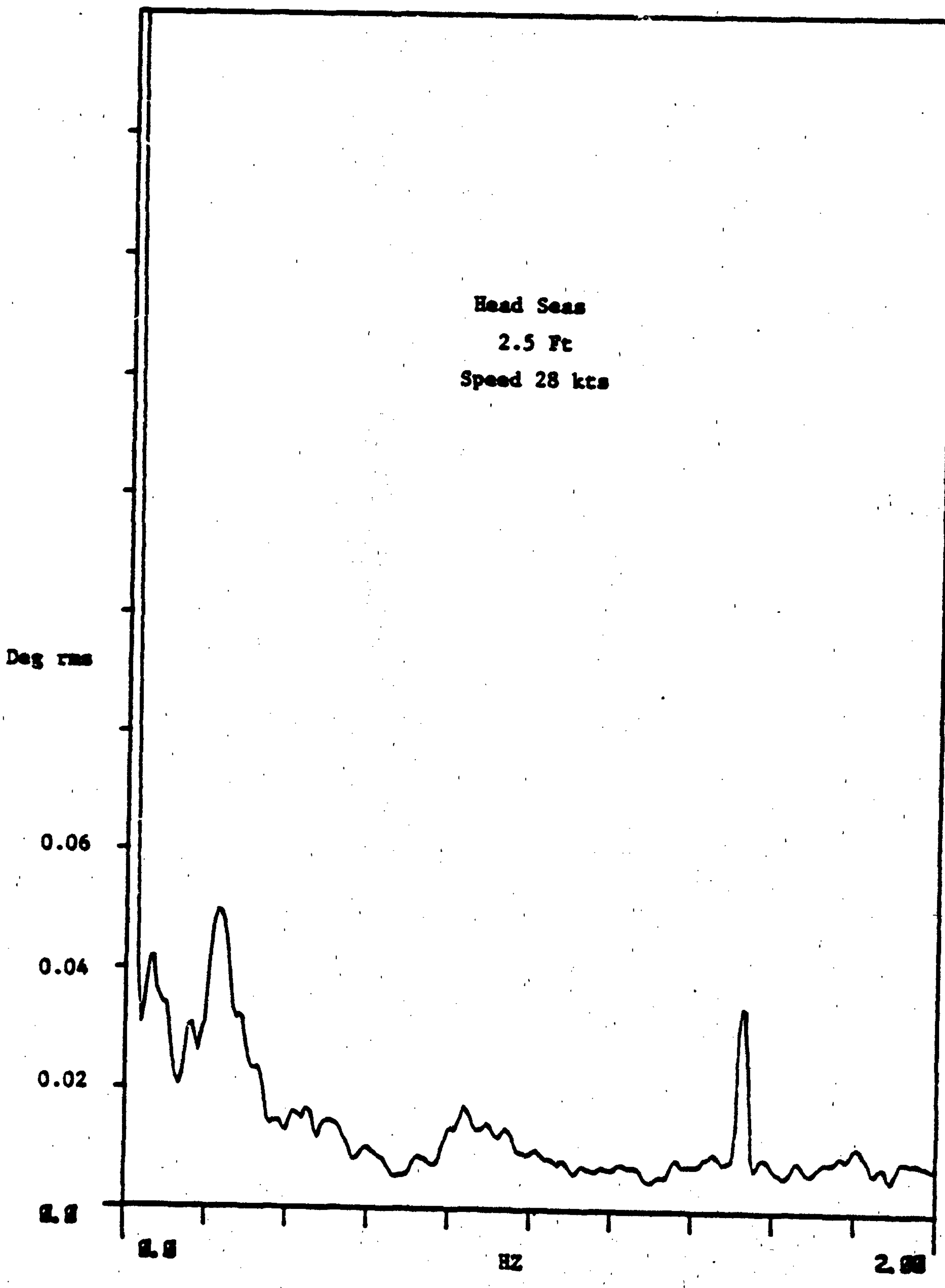

Figure B17. ROLL SPECTRUM, CGC SHEARWATER

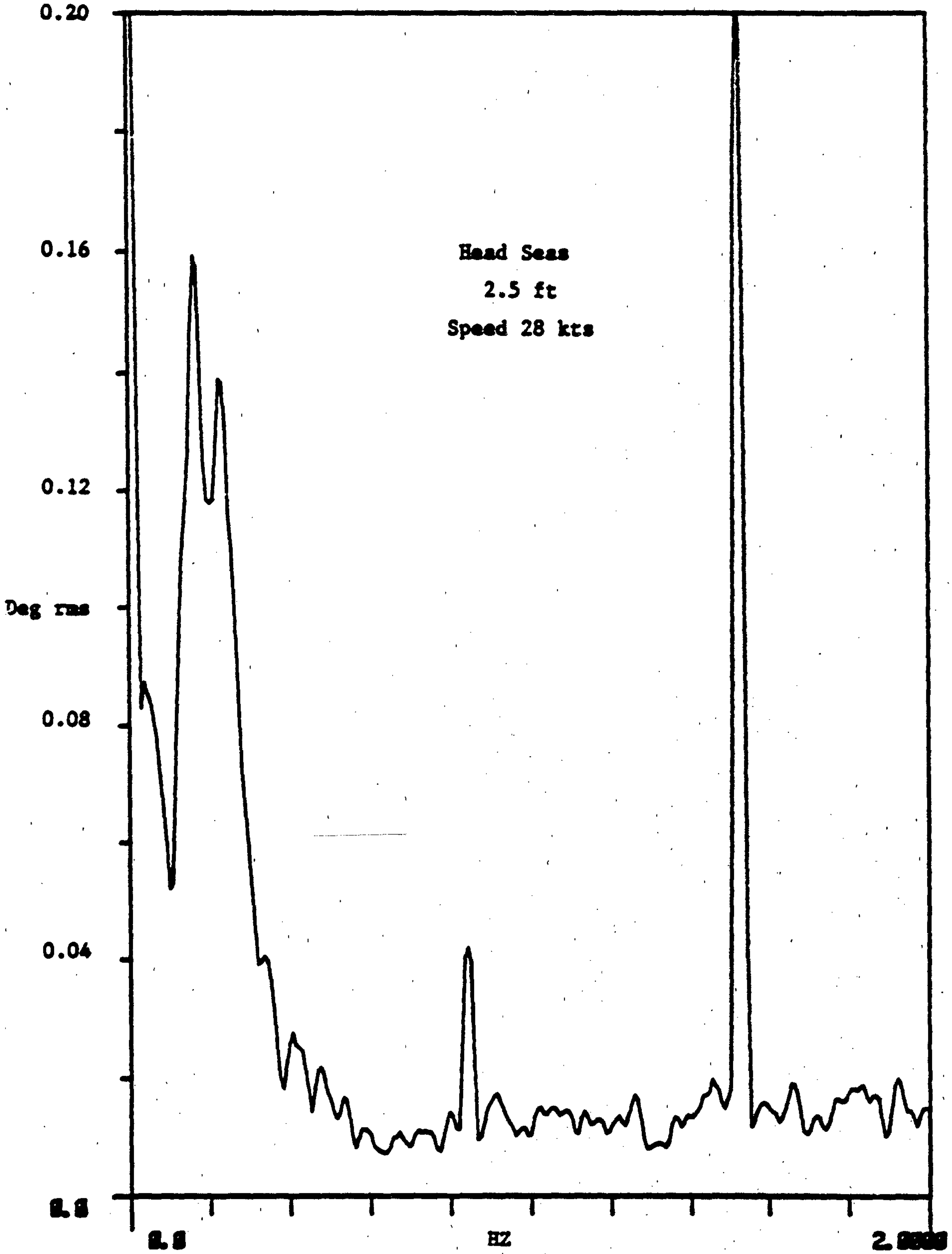

FIGURE B18. PITCH SPECTRUM, CGC SHEARWATER

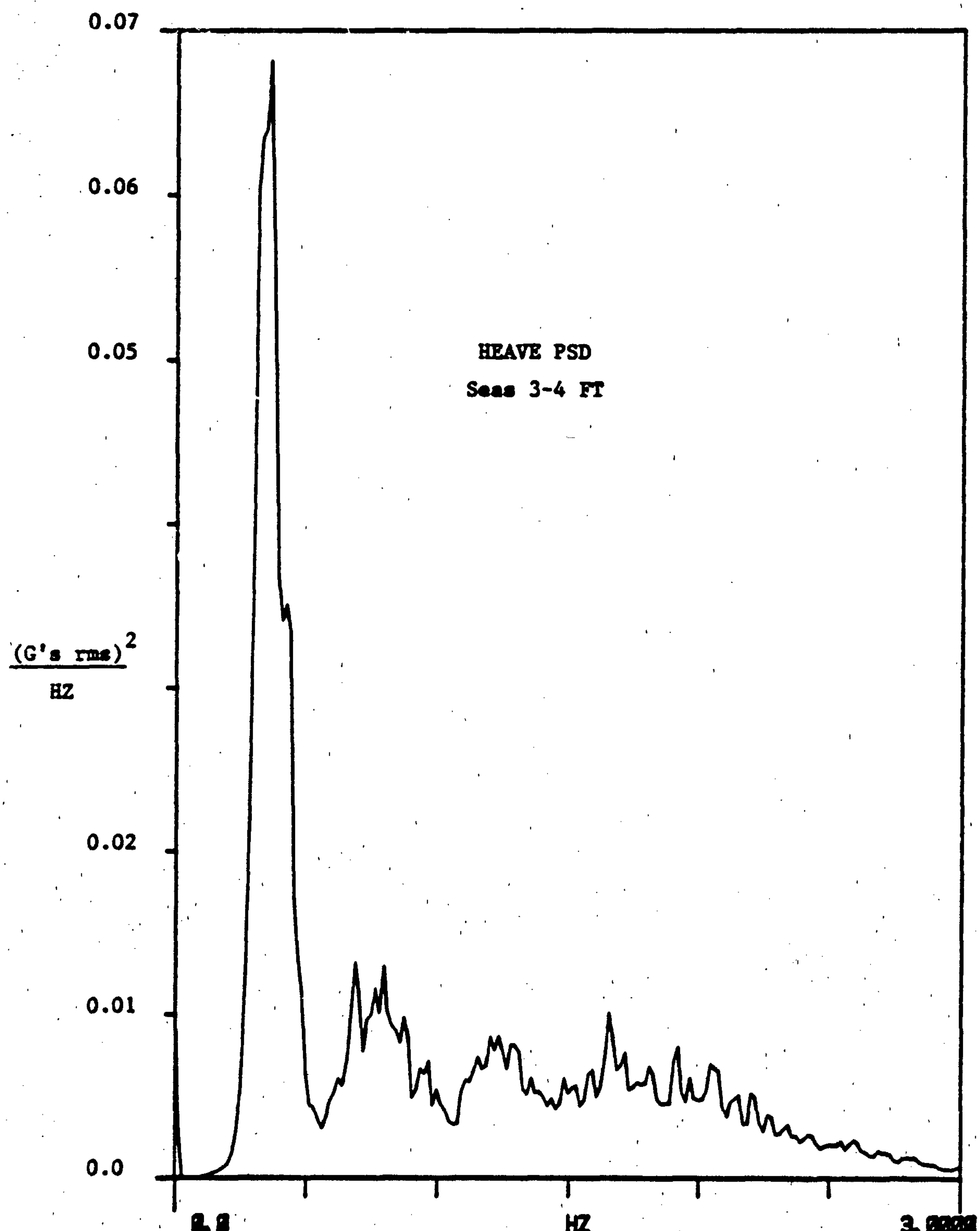

FIGURE B19. HEAVE PSD, CGC SEA HAWK (17 kts HEAD SEAS)

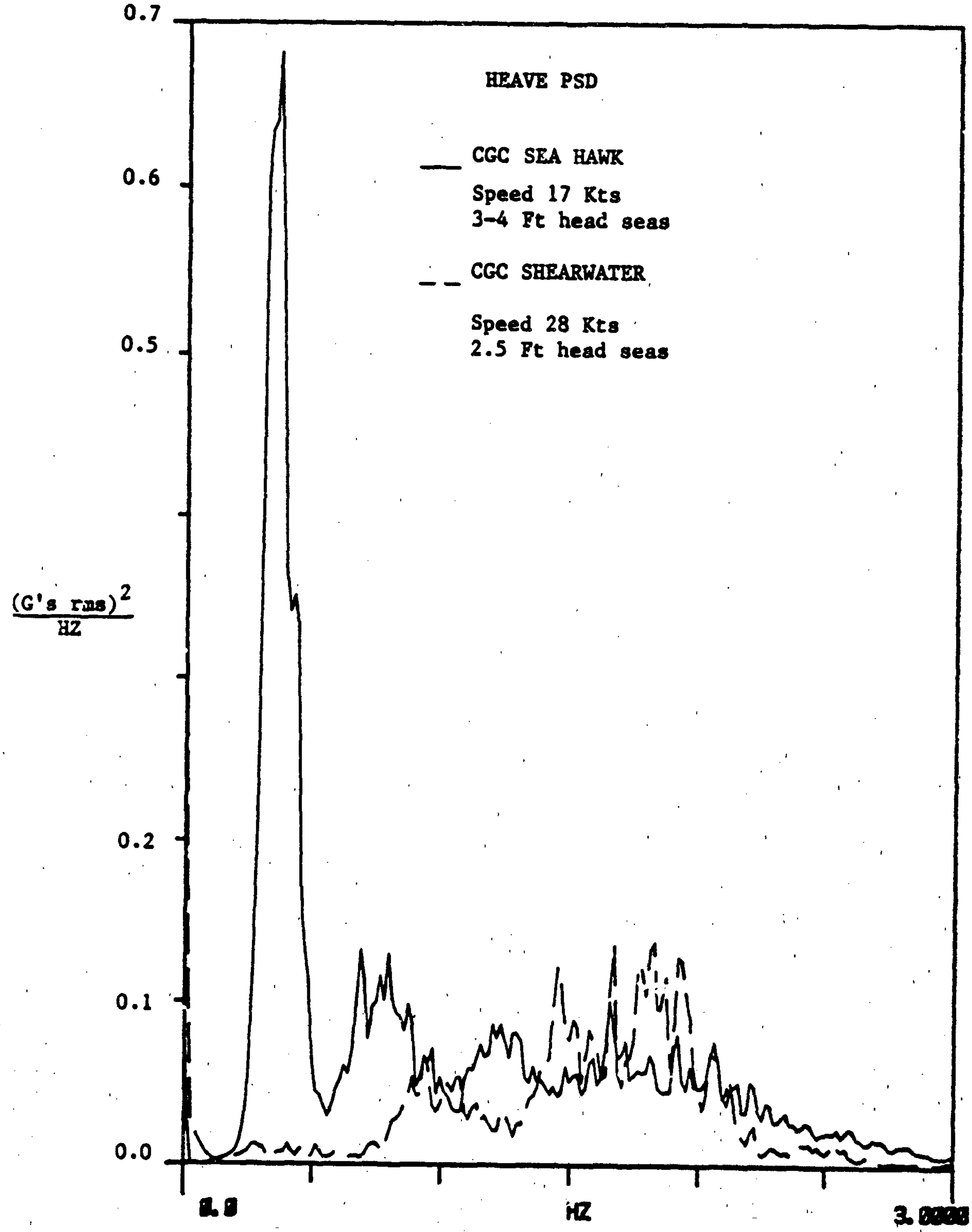

FIGURE B20. HEAVE PSD'S, CGC SHEARWATER & CGC SEA HAWK

APPENDIX C

MEASURING HUMAN RESPONSE TO VERTICAL ACCELERATIONS

The limits shown in Table 1 and Figure 2a in reference (a) are "fatigue-decreased proficiency boundary" values for vibration acceleration in the A_z direction (foot- or buttocks-to-head direction). These limits are valid for discrete frequency (1/3 octave band) vibrations acting on a person. When vibration occurs simultaneously at more then one discrete frequency within the range of 1 to 80 HZ, the rms acceleration of each frequency component shall be evaluated separately with reference to the appropriate limit at that band. The heave signals from the SES's which are being evaluated are broad band (multiple) frequencies between 1 and 4 HZ.

Amendment 1 to reference (a) states that "Recent research on comfort and on performance has shown that where vibration spectrum consists of several vibration components or is a broad-band motion the weighted method often provides a good approximation to the effects of motion. Therefore, when a single number is desired to quantify the effect of vibration of this type for a single axis, the weighting method is now recommended in preference to the rating method. However, when overall weighted values of acceleration are reported, it is recommended that the frequency composition of the motions should also be quoted. The overall weighted value is primarily recommended for comparison with the overall weighted value of other vibrations. For direct comparison of these values with the guidance given in the tables and figures appropriate adjustment of these values may have to be considered."

The weighted method as stated above is preferred to characterize a vibration environment with respect to its effects on people by a single quantity for the range of 1 to 80 HZ.

This is accomplished with an electronic weighted network. This is the type of measurement utilized by the Bruel & Kjaer Human Response Vibration Meter. The overall weighted vibration values measured are to be compared to the permissible values in the 4 to 8 HZ band for vertical acceleration. Table C1 lists the applicable weighting factors. As you can see, they are referenced to the 4 to 8 HZ range which is the most sensitive.

It is appreciated that this proposed method for a single number characterization of a vibration environment and for comparison of this number with the exposure criteria is an approximation. The weighting method results in an over-conservative assessment of the effects of vibration. That is depending on the vibration spectrum the permissible weighted vertical accelerations could be raised above the values determined by the most sensitive frequency band. This was the case when comparing limits from both methods, weighting using the human response meter and discrete 1/3 octave band analysis. In all cases, the human response meter computed exposure and decreased proficiency limits significantly shorter (and more conservative) in time than the times for the most sensitive discrete 1/3 octave band analysis method.

TABLE C1

WEIGHTING FACTORS RELATIVE TO 4-8 HZ

The frequency range of maximum acceleration sensitivity for the response curves of Figure 10.

Frequency (center frequency one third octave band) HZ	Weighting Factors for Longitudinal Vibrations (Vertical)
1.0	0.50 = -6 dB
1.25	0.56 = -5 dB
1.6	0.63 = -4 dB
2.0	0.71 = -3 dB
2.5	0.80 = -2 dB
3.15	0.90 = -1 dB
4.0	1.00 = 0 dB
5.0	1.00 = 0 dB
6.3	1.00 = 0 dB
8.0	1.00 = 0 dB
10.0	0.80 = 2 dB
12.5	0.63 = -4 dB
16.0	0.50 = -6 dB
20.0	0.40 = -8 dB
25.0	0.315= -10dB
31.5	0.25 = -12dB
40.0	0.20 = -14dB
50.0	0.16 = -16dB
63.0	0.125= -18dB
80.0	0.10 = -20dB

TABLE C2

CGC SHEARWATER ACCELERATIONS
1/3 OCTAVE BAND ANALYSIS

One Third Octave Center Band Frequency (HZ)	Vertical Acceleration (G's rms) Head Seas	Vertical Acceleration (G's rms) Bow Quarter Seas
1.00	0.0337	0.0163
1.25	0.0318	0.0193
1.60	0.0567	0.0321
2.00	0.0569	0.0333
2.50	0.0212	0.0173
3.15	0.0105	0.0100

2 Dec 1982
Speed 28 knots
Seas 2.5 feet
Accelerations measured on Mess Deck (see Figure 1)

TABLE C3

CGC SEA HAWK ACCELERATIONS
1/3 OCTAVE BAND ANALYSIS

One Third Octave Center Band Frequency (HZ)	Vertical Acceleration (G's rms) Head Seas
1.00	0.0359
1.25	0.0449
1.60	0.0480
2.00	0.0496
2.50	0.0354
3.15	0.0185

25 Nov 1983
Speed 17 knots
Head Seas 3-4 feet
Accelerations measured on Bridge (see Figure 2)

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